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Investigating and Characterising the Coupling of LEGO and 3D Printing

Investigating and Characterising the Coupling of LEGO and 3D Printing

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Abstract

The importance and impact of prototyping in the design process cannot be overstated. It allows designers to test, communicate, and develop their ideas – pushing forward the design. The two largest factors limiting the use of prototypes are the fabrication time and costs. Addressing these enables earlier, and more frequent prototyping in the design process – producing better product outcomes.

While many efforts have addressed this through the creation of prototyping frameworks, few have focussed on the tools used. From an extensive literature review, the need for a prototyping technique that can rapidly and cheaply fabricate prototypes at suitable levels of fidelity is identified. This is supported by the findings from a preliminary study comparing prototyping techniques in a design task.

This thesis reports the development and characterisation of a solution to fulfil this need: Hybrid Prototyping (HP). HP couples two different prototyping techniques to complement their benefits and mitigate their limitations. LEGO and 3D printing were the techniques chosen as they have opposing fabrication times and costs, but possess some common properties that aid their coupling. Through this combination, with LEGO forming the bulk of the prototype and 3D printing providing high fidelity parts, the fabrication time and material usage of form-based prototypes have the potential to be significantly reduced.

This LEGO and 3D printing instantiation of HP was demonstrated and validated in a series of real-world prototypes. The different HP strategies were benchmarked against 3D printing, showing that the cumulative fabrication time could be reduced by 56 % and the material usage reduced by 76 %.

The contributions to knowledge consist of the overall HP methodology, the characterisation of the coupling of LEGO and 3D printing, and the demonstration of HP. Further work considers the use of HP in the design process and how the tool can be improved.

Acknowledgements

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Finally, I am eternally grateful to my fiancée Thea for always being by my side, bringing welcome respite with holidays to distant and not-so-distant places. This thesis is the result of her support, patience and encouragement.

Author's Declaration

"I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author."

SIGNED:.. DATE:.................

Publications

Listed here are the publications that have been produce over the course of the research presented in this thesis. Their respective abstracts can be found in Appendix B.

Journal

Mathias, D., Snider, C., Hicks, B., and Ranscombe, C. *Accelerating product prototyping through hybrid methods: Coupling 3D printing and LEGO*. in: *Design Studies* 62 (2019), pp. 68–99. DOI: `10.1016/j.destud.2019.04.003`

Ranscombe, C., Bissett-Johnson, K., **Mathias, D.**, Eisenbart, B., and Hicks, B. *Designing with LEGO: exploring low fidelity visualization as a trigger for student behavior change toward idea fluency*. In: *International Journal of Technology and Design Education* (2019). DOI: `10.1007/s10798-019-09502-y`

Conference

Mathias, D., Hicks, B., and Snider, C. *Hybrid Prototyping: Pure Theory or a Practical Solution to Accelerating Prototyping Tasks?* In: *Proceedings of the Design Society: International Conference on Engineering Design*. Vol. 1. 1. Delft, Netherlands, 2019, pp. 759–768. DOI: `10.1017/dsi.2019.80`

Mathias, D., Hicks, B, Snider, C, and Ranscombe, C. *Characterizing the Affordances and Limitations of Common Prototyping Techniques to Support the Early Stages of Product Development*. In: *International Design Conference - Design 2018*. Dubrovnik, Croatia, 2018, pp. 1257–1268

Mathias, D., Boa, D., Hicks, B. J., Snider, C., Bennett, P., and Taylor, C. *Design Variation through Richness of Rules Embedded in LEGO Bricks*. In: *Proceedings of 21st International Conference on Engineering Design, ICED 2017*. Vol. 8. August. Vancouver, Canada, 2017, pp. 99–108

Ranscombe, C., Zhang, W., Rodda, J., **and Mathias, D.** *Digital Sketch Modelling: Proposing a Hybrid Visualisation Tool Combining Affordances of Sketching and CAD*. in: *Proceedings of the Design Society: International Conference on Engineering Design*. Vol. 1. 1. Delft, Netherlands, 2019, pp. 309–318. DOI: `10.1017/dsi.2019.34`

Boa, D., **Mathias, D.**, and Hicks, B. *Evolving lego: Prototyping requirements for a customizable construction kit*. In: *Proceedings of 21st International Conference on Engineering Design, ICED 2017*. Vol. 4. DS87-4. The Design Society: Vancouver, Canada, 2017, pp. 297–306

Goudswaard, M., Hicks, B. J., Nassehi, A., **and Mathias, D.** *Realisation of self-replicating production resources through tight coupling of manufacturing technologies*. In: *Proceedings of 21st International Conference on Engineering Design, ICED 2017*. Vol. 5. Vancouver, Canada, 2017, pp. 31–40

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Definitions

AF	Adapted Fidelity Hybrid Prototyping
AM	Additive Manufacturing
API	Application Programming Interface
CAD	Computer Aided Design
CNC	Computer Numerically Controlled
CSG	Constructive Solid Geometry
DF	Distributed Fabrication Hybrid Prototyping
DfAM	Design for Additive Manufacture
DfFA	Design for Fabrication and Assembly
DfMA	Design for Manufacture and Assembly
FDM	Filament Deposition Modelling
GUI	Graphical User Interface
HP	Hybrid Prototyping
NPD	New Product Development
RF	Reuse Focussed Hybrid Prototyping
ROI	Region of Interest
RQ	Research Question
STL	Stereolithography/Standard Tessellation Language

Chapter 1

Introduction

1.1 Introduction

Prototyping is one of the most critical activities in the design and development of new products [9]. Few – if any – design activities in the development process are conducted without prototyping. These prototypes can take a broad range of forms; from simple sketches to detailed analytical simulations, from crude cardboard models to fully functional pre–production prototypes. Prototypes allow designers to test, develop, and communicate their ideas – informing important design decisions throughout the design process.

It is widely accepted that increased prototyping efforts benefit both individual designers and design teams [10], and lead to improvements in the product development process, resulting in more successful products [11], [12]. An iconic example is the success of Dyson's cyclonic vacuum cleaner, which was finally achieved after 5,127 prototypes [13].

As the design process is domain dependent and can be applied in the development of many different products or services, different industries approach prototyping in different ways. Firms developing large, complex systems (e.g. aircraft) tend to use prototyping to test against specifications, while smaller, more agile companies focus on prototyping as a way to explore and develop a new concept (e.g. consumer products) [14].

Correspondingly, a multitude of prototyping tools and techniques are used and have been developed specifically to support prototyping [4]. Figure 1.1 shows some examples of different prototyping tools. Examples include 3D printing enabling designers to physically interact with their designs [15], the use of cardboard prototypes [16], and using construction kits to engage with non–technical stakeholders and foster co-design [7].

Figure 1.1 Examples of different prototyping techniques

[9] Wall, M. B. et al. (1992) *Evaluating prototyping technologies for product design*
[10] Gerber, E. (2009) *Prototyping: Facing uncertainty through small wins*
[11] Menold, J. et al. (2017) *Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[13] James Dyson Foundation. (2010) *Engineering Box - Teacher's Pack*
[14] Schrage, M. (1993) *The Culture(s) of Prototyping*
[4] Mathias, D. et al. (2018) *Characterizing the Affordances and Limitations of Common Prototyping Techniques to Support the Early Stages of Product Development*
[15] Das, A. K. (2004) *CAD and rapid prototyping as an alternative of conventional design studio*
[16] Kim, W.-s. (2009) *Advanced Kinematic Cardboard Prototyping for Robot Development*
[7] Boa, D. et al. (2017) *Evolving lego: Prototyping requirements for a customizable construction kit*

In 1998, Thomke [17] showed the importance of prototyping effectively through the reduction of cost and time. Despite the prototyping research since, and the development of novel prototyping techniques and frameworks, the two largest factors limiting the use of prototypes are still the time and cost to produce them [18], [19]. Dahan and Mendelson [20] argued that every 'test' (i.e. prototype) required some cost or time to produce and that managing the allocation of these resources is crucial to the success of the product. Prototype production time and costs are explored further in Section 2.4. Reducing the cost and time to create a prototype enables earlier, and more frequent, prototyping in the design process [12]. Bringing prototyping earlier into the design process can result in stimulating innovation [21], reducing design fixation [22], accelerating the process [23], and producing better product outcomes [24].

While there are many factors in the development of successful products, Ullman [25] states that the design process has the largest impact on a product's cost, time to market, and desirability. Where 75 % of the product cost is committed early in the design process, meaning that decisions made in these stages can have a disproportionately large impact on the overall cost of development. This is illustrated in Figure 1.2.

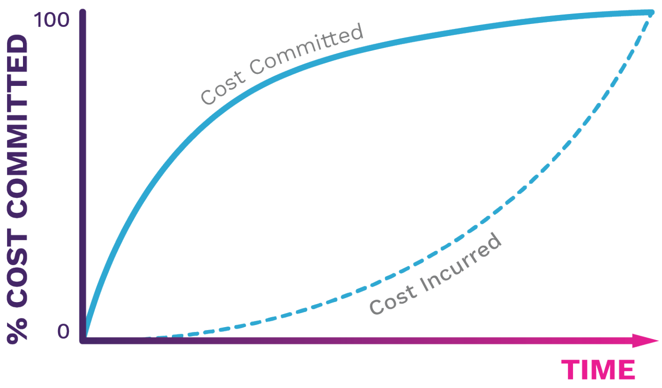

Figure 1.2 Percentage of product cost commited during the design process (adapted from Ullman [25])

While prototyping is used throughout the design process (see Section 1.3), the front-loading of costs means that positioning prototyping efforts to answer key design questions and decisions early within the overall product development process is critical [12] –

[17] Thomke, S. H. (1998) *Managing Experimentation in the Design of New Products*
[18] Camburn, B. et al. (2015) *A Systematic Method for Design Prototyping*
[19] Otto, K. and Wood, K. (2001) *Product Design: Techniques in Reverse Engineering and New Product Development*
[20] Dahan, E. and Mendelson, H. (2001) *An Extreme-Value Model of Concept Testing*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[21] Viswanathan, V and Linsey, J. (2010) *Physical Models In Idea Generation – Hindrance Or Help*
[22] Youmans, R. J. (2011) *The effects of physical prototyping and group work on the reduction of design fixation*
[23] Neeley, L. W. et al. (2013) *Building fast to think faster: exploiting rapid prototyping to accelerate ideation during early stage design*
[24] Yang, M. C. (2005) *A study of prototypes, design activity, and design outcome*
[25] Ullman, D. G. (2003) *The Mechanical Design Process*

particularly during the first 30 % of the design process [26].

This thesis investigates how improving prototyping could improve the design process by reducing the fabrication time and the cost of prototypes. In this introduction, prototyping is defined from existing literature and contextualised within the design process. The requirements of prototyping are established from models of the design process and methods for their improvement posited. The overall motivation and general aim of the thesis are given, and the chapter finishes by laying out the structure of the thesis, and subsequent chapters.

1.2 Prototyping

Despite being an essential part of the design process, there is no overarching definition for a *prototype* [27]. Typically, a prototype is considered to be a physical approximation of the product being designed (i.e. a design artefact). This concept of a prototype as a design artefact is reflected by Otto and Wood [19], who define a prototype as:

> "a physical instantiation of a product, meant to help resolve one or more issues during the product development."

However, this is a narrow definition of a prototype. Prototyping is more than the production of a design representation to be tested or evaluated. The act of prototyping helps designers supplement their mental models of the design problem [10], answer questions about their design solution [24], and communicate with stakeholders [28]. A more general definition for prototyping that encompasses both the output (the prototype as a design artefact), and the process (the act of prototyping) is give by Camere and Bordegoni [29]:

> "the activity of engaging with the product-to-be, instantiating the design process."

This definition emphasises the importance of prototyping in the design process and highlights the intertwined nature of prototyping and design.

Just as design activities develop and progress from conceptual exploration of the design space to generating detailed technical drawings (see Section 1.3), so too do prototypes. Correspondingly, these prototyping tools need to develop and progress to support the required design activities. A key part of this dynamic nature of prototyping is its purpose – what is the reason for creating the prototype? According to Jensen *et al.* [27], a prototype can have two fundamental purposes:

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[26] Elsen, C. et al. (2012) *Representation in Early Stage Design: An Analysis of the Influence of Sketching and Prototyping in Design Projects*
[27] Jensen, L. S. et al. (2016) *Prototypes in engineering design: definitions and strategies*
[19] Otto, K. and Wood, K. (2001) *Product Design: Techniques in Reverse Engineering and New Product Development*
[10] Gerber, E. (2009) *Prototyping: Facing uncertainty through small wins*
[24] Yang, M. C. (2005) *A study of prototypes, design activity, and design outcome*
[28] Boujut, J.-F. and Blanco, E. (2003) *Intermediary Objects as a mean to foster Co-operation*
[29] Camere, S. and Bordegoni, M. (2016) *A lens on future products: An expanded notion of prototyping practice*

- A divergent tool for ideation and synthesis that allows the designer to explore the design space and embody their concepts.
- A convergent tool for evaluation and selection that allows the designer to test their design against specifications and requirements.

In order to meet these different purposes, prototypes and prototyping tools need to have a set of general requirements. These requirements are outline in Section 1.2.1

The following sections contextualise where prototyping is used in the design process and the types of products that this thesis will be focussing on. Further definitions of prototyping in literature and how prototypes are used in the design process are explored in more depth in Chapter 2.

1.2.1 Prototyping Objectives

Prototyping is considered to be one of the most important design tools within the design process [30]. Correspondingly, the prototyping process and prototyping techniques have high–level objectives that need to reflect the goal of their use as design tools. Camburn *et al.* [12] shows that the objectives can be split into *activity* and *process* objectives that meet the dual nature of prototyping as both a design activity and a design artefact. Table 1.1 outlines these objectives. Activity objectives consider the design activities that prototyping supports, while process objectives consider the effort of creating a prototype.

Table 1.1 Summary of the two categories of prototyping objectives

Activity Objectives	Process Objectives
Refinement	Reduce Time
Exploration	Reduce Cost
Active Learning	
Communication	

In Section 1.3, these high–level objectives are compared against design process models to show how prototypes can support the development of new products. The objectives are expanded and discussed further in Sections 1.3.1 and 1.3.2.

As different prototyping techniques have different affordances and limitations in their use (see Section 2.3), their suitability to match the different objectives varies. As a result, a single prototyping technique cannot be expected to meet every objective. To address this, Camburn *et al.* [12] offer several different approaches to focus prototyping efforts to achieve particular objectives.

[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*

1.2.2 Manifestation of Prototyping

Prototyping is used throughout the design process (see Section 1.3), and is used in the design of a broad range of products and services. How prototypes manifest in the design process varies by the type of product being designed and the stage of the design's progression. These two areas are described in more detail in the following sections.

Types of Product

Although prototyping can be used to design services (and software), this thesis will be focussing on discrete, physical products that have to be designed and then manufactured. Ulrich and Eppinger [30] state that products lie between two ends of a continuum: *technology–driven* products at one end, *user–driven* products at the other. The ends of this continuum are defined as:

- *Technology–driven* products – the core tenet of these products is based on its technology, or ability to achieve a particular technical task. These products are predominantly bought for their technical performance, rather than aesthetic or ergonomic requirements. e.g. a computer hard drive.
- *User–driven* products – the benefit of these products is generated from its functionality of interfaces and aesthetic appeal. There is usually a high degree of user interaction in these products, and the external appearance is used to differentiate between competitors. User–driven products can be technically sophisticated, however this is not usually a differentiator. e.g. a wristwatch.

Figure 1.3 shows some common products on this continuum.

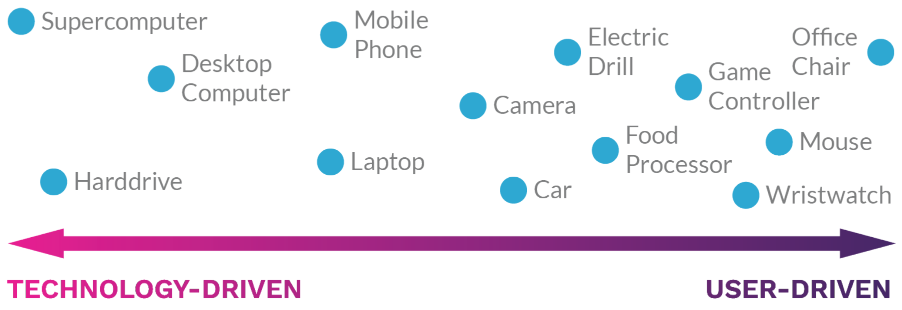

Figure 1.3 The classification of some common products on the continuum of technology–driven to user–driven. (adapted from Ulrich and Eppinger [30])

Prototyping is used in the design of products at any point along the continuum [12], [31]. However, in *technology–driven* products, the design and evaluation of the functional aspects require prototypes that allow designers to explore and test the specific technical phenomena [30]. Consequently, the prototypes are bespoke to the functionality of a particular product. In the design of *user–driven* products, while the appearance and shape

[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[31] Buchenau, M. and Suri, J. (2000) *Experience Prototyping*

will be unique to each product, the prototyping efforts and tools used will have significant overlap and similarities – even between different types of products [30].

Therefore, this thesis will be focussing on *user–driven* products (e.g. household appliances and consumer electronics) as research into form–based prototypes is more generalisable than function–based ones.

Progression of the Design

Prototypes take on many forms in order to match the progression of the design solution as it advances through the design process. Ullman [25] defines four types of prototype based on their level of progression of the design:

- A *Proof–of–Concept* prototype is used to identify what approach to take in the initial stages when designing a new product.
- A *Proof–of–Product* prototype helps develop the physical embodiment and manufacturing viability.
- A *Proof–of–Process* prototype demonstrates that the chosen materials and production methods meet the product requirements.
- A *Proof–of–Production* prototype shows that the complete production process can achieve the required results.

These prototype progressions can be aligned with the phases of the design process and are considered further in Section 1.3

Using Ullman's classification of prototypes, this thesis will be predominantly focussing on *proof–of–concept* prototypes that are used in the early stages of the design process. As 75 % of the product development costs are committed early in the design process [25], decisions made in these stages can have a disproportionately large effect on the overall cost. Figure 1.2 shows how the cost committed and the cost incurred vary over the course of the design process. It follows that by investigating *proof–of–concept* prototypes, there is potential to improve the use and frequency of prototyping in the early stages of the design process. The sooner design teams can identify problems, the more time to iterate solutions and build better products [26].

1.3 Prototyping in the Design Process

Every product, however simple, undergoes a process that takes it from idea to market. This process is called the New Product Development process (NPD). Within NPD is the design process. The design process can be considered to be the steps performed to reach a final design description from a design problem. Ullman [25] states that the design process has the largest impact on a product's cost, and time to market, with 85 % of the problems new products face arising from a poor design process.

[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*
[25] Ullman, D. G. (2003) *The Mechanical Design Process*
[26] Elsen, C. et al. (2012) *Representation in Early Stage Design: An Analysis of the Influence of Sketching and Prototyping in Design Projects*

Cross [32] breaks the design process down into four general stages based on the essential activities that the designer performs. This model is shown in Figure 1.4.

Figure 1.4 A simple descriptive model of the four stages of the design process (adapted from Cross [32])

Typically, the problems designers face are 'ill-defined' where the goals are vague, with potentially many 'correct' answers, and there is no clear way to proceed. This ambiguity and uncertainty is often called the Fuzzy Front End (FFE) of design [33] and it is important that designers find the 'right' problem to solve [34]. Therefore, the process begins with the *exploration* of the problem space, where the designers attempt to improve the definition of the problem and create a design specification to quantify. From this, the designers *generate* design concepts as potential solutions to the problem. The concepts are *evaluated* against the design specification: if the design meets the requirements the process can continue on to the *communication* of the final design, otherwise a different design needs to be chosen and an iterative feedback loop is formed. Iteration is an important and ubiquitous characteristic of the design process resulting in a progressive knowledge generation process and enabling the incorporation of changes as the design develops [35]. Overall, the end goal of the design process is to *communicate* a specific and clear design description to the manufacturer, at which point the production process can commence.

At every stage of this iterative process, prototypes can be used to support the activities the designers are performing [11]; whether it is communicating ideas [36], exploring design concepts [37], eliciting user feedback [38], or evaluating decisions [30].

1.3.1 Descriptive Models

Cross' four stages of the design process (See Figure 1.4) describes the heuristic sequence of design activities that are generally undertaken by designers. This is a simple *descriptive* model of the design process.

Descriptive models of the design process describe the actions and activities designers perform. Typically, the different models posited vary in the level of detail provided but

[32] Cross, N. (2008) *Engineering Design Methods*
[33] Kim, J and Wilemon, D. (2002) *Focusing The Fuzzy Front- End In New Product Development*
[34] Savoia, A. (2011) *Pretotype It*
[35] Wynn, D. C. and Eckert, C. M. (2017) *Perspectives on iteration in design and development*
[11] Menold, J. et al. (2017) *Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design*
[36] Carlile, P. R. (2002) *A Pragmatic View of Knowledge and Boundaries: Boundary Objects in New Product Development*
[37] Dow, S. et al. (2011) *The effect of parallel prototyping on design performance, learning, and self-efficacy*
[38] Kershaw, T. et al. (2011) *The Effect of Prototyping and Critical Feedback on Fixation in Engineering Design*
[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*

largely describe the same flow of activities (e.g. French [39]). This focusses the model on the *process* and what the designer should be doing (e.g. *exploring* in Cross' model, Figure 1.4). The motivation for modelling the design process is stated by the Design Council [40]:

> "the management of the design process through more formalised models is key to its effectiveness."

A more formalised model allows a designer to reflect on their design behaviour to understand what they should be doing during different aspects of the design process.

Design Council [40] developed the Double Diamond model to clarify and formalise the design activities. The name arises from two consecutive divergent and convergent activities, as shown in Figure 1.5, that occur between the inputs and outputs. The model's input is the *problem*, this is researched and analysed to produce a *definition* (e.g. design specification), this is then used to iterate and test designs to create the *solution* – the model's output.

It emphasises the importance of understanding the design problem, and encourages the designer to thoroughly *discover* and *define*. This ensures that the fully–understood design problem is solved and a suitable set of requirements and constraints is generated.

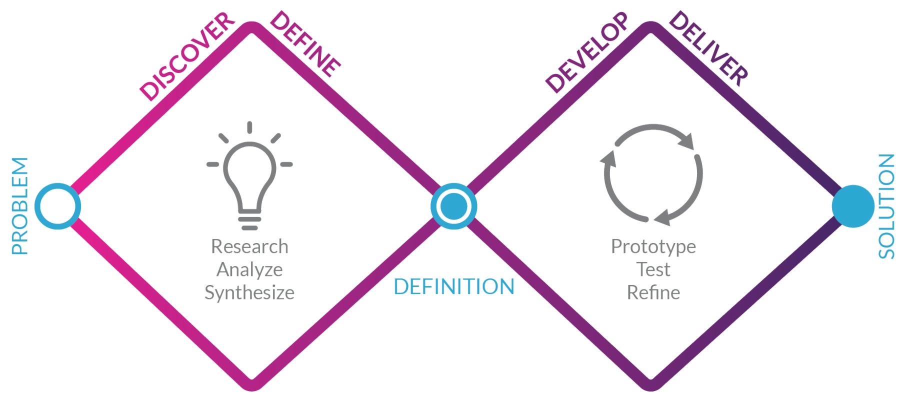

Figure 1.5 The Double Diamond descriptive model of the design process (adapted from Design Council [40])

The four phases of the Double Diamond design process align with Cross' model but provide intent and direction to the activities described (c.f. Figure 1.4 and Section 1.3.2). The phases are as follows:

1. Discover (*Divergent*) – The task is clarified in this phase through the exploration of the problem space and identification of all the possible design requirements.
2. Define (*Convergent*) – A design specification is synthesised from establishing the essential problems and distilling the requirements into a performance–based list of specifications.
3. Develop (*Divergent*) – Possible solutions to meet the performance specification are evaluated, iterated and combined to develop a more complete design.

[39] French, M. (1999) *Conceptual Design For Engineers*
[40] Design Council. (2007) *Eleven lessons: managing design in eleven global companies.*

4. Deliver (*Convergent*) – The chosen design is consolidated into a final specification detailing operation and manufacture, to be communicated to the manufacturers.

Jensen *et al.* [27] offer two fundamental purposes of a prototype:

- A *divergent* tool for ideation and synthesis that allows the designer to explore the design space and embody their concepts.
- A *convergent* tool for evaluation and selection that allows the designer to test their design against specifications and requirements.

These purposes neatly align with the sequence of divergent–convergent activities described by the Double Diamond model – further emphasising the interwoven nature between design and prototyping.

Activity Objectives for Prototyping

The objectives for prototyping were introduced in Section 1.2.1, this section shows how the *activity* objectives compare against descriptive models of the design process.

The activity objectives were identified as emergent categories through literature analysis by Camburn *et al.* [12].

- *Refinement* – gradually improving a design
- *Exploration* – seeking out new design concepts.
- *Active Learning* – gaining new knowledge about the design space or relevant phenomena.
- *Communication* – sharing information about the design, and its potential use within the design team and to users.

These objectives can be compared to the four stages of Cross' general design process (see Figure 1.4):

- *Exploration* – aligns with the exploration objective
- *Generation* – aligns with the exploration and active learning objectives
- *Evaluation* – aligns with the refinement and active learning objectives
- *Communication* – aligns with the communication objective

There is no single prototyping tool that can meet all these objectives, and therefore all the stages of design activity [41]. As a result, many different prototyping tools are used to support different design activities [17], [42]. For example, sketching is used when generating concepts [43] or highly–finished foam models are used to communicate with

[27] Jensen, L. S. et al. (2016) *Prototypes in engineering design: definitions and strategies*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[41] Jang, J. and Schunn, C. D. (2012) *Physical Design Tools Support and Hinder Innovative Engineering Design*
[17] Thomke, S. H. (1998) *Managing Experimentation in the Design of New Products*
[42] Shih, Y. T. et al. (2017) *Using suitable design media appropriately: Understanding how designers interact with sketching and CAD modelling in design processes*
[43] Sachse, P. et al. (2003) *Support value of sketching in the design process*

stakeholders [44].

1.3.2 Prescriptive Models

Prescriptive design models typically employ a systematic approach to the design process, using explicit phases and activities with clear input and outputs. They are typically *product* focussed models (as opposed to *process* focussed in descriptive models), where the emphasis is on the state of the design solution.

Figure 1.6 shows the model for the Systematic Approach to Design [45]. Other prescriptive models include VDI 2221 [46] and Pugh's Total Design [47]. Pahl and Beitz' model is explicit with specific inputs and outputs (state of the design solution) to each of the design stages. They suggest the types of activities required to develop the design and produce the output. Furthermore, it highlights the necessity for feedback and iteration in the design process with later stages impacting earlier ones.

Figure 1.6 also shows Pahl and Beitz' four phases of the design process. These are used as umbrella terms to explain the developmental state of the design solution and to broadly cover the activities performed at that point in the design process.

Pahl and Beitz [45] state that prototypes were deliberately excluded from their design process model (see Figure 1.6) because the information they provide could be needed at any point in the process and their use is domain dependent. As a result, prototypes could not be associated with a particular phase. It is possible to link existing definitions of types of prototypes (i.e. Ullman [25], see Section 1.2.1) to Pahl and Beitz' phases of the design process.

Design Phases

An aspect common to most design models (particularly prescriptive ones) is the concept of design phases that reflect the types of design activity and the progression of the design solution through the design process.

The following four phases are taken from Pahl and Beitz [45] and align with those described by French [39] (analysis of the problem, conceptual design, embodiment of schemes, and detailing) and Baxter [48] (business opportunity, design specifications, concept design, embodiment design, detail design, and design manufacture). The phases are:

1. Clarification of the Task
2. Conceptual Design
3. Embodiment Design

[44] Hallgrimsson, B. (2012) *Prototyping and Modelmaking for Product Design*
[45] Pahl, G. and Beitz, W. (1984) *Engineering Design*
[46] Jänsch, J and Birkhofer, H. (2006) *The development of the guideline VDI 2221 - the change of direction*
[47] Pugh, S. (1990) *Total design : integrated methods for successful product engineering*
[25] Ullman, D. G. (2003) *The Mechanical Design Process*
[39] French, M. (1999) *Conceptual Design For Engineers*
[48] Baxter, M. (1996) *Product Design: Practical Methods for the Systematic Development of New Products*

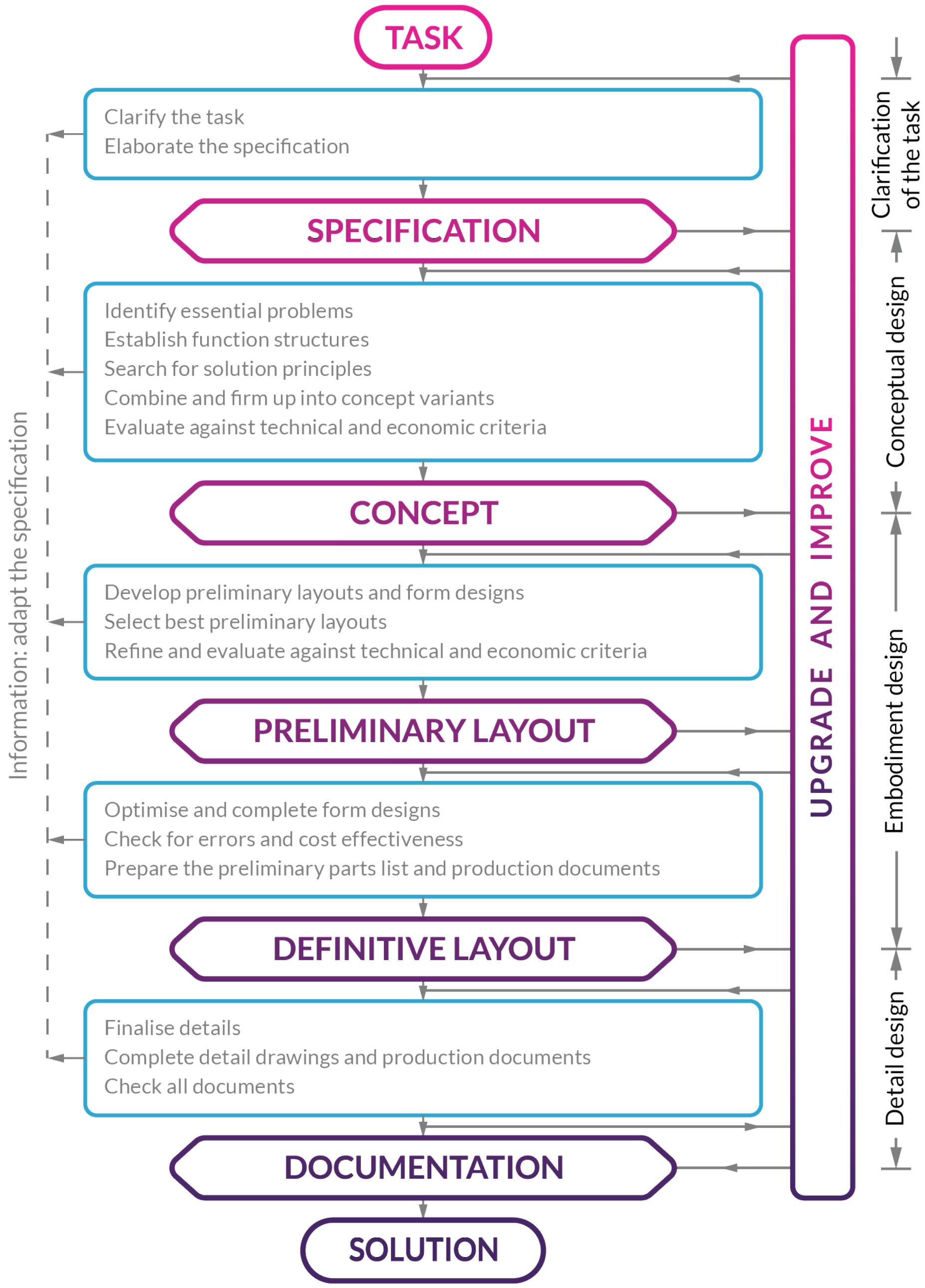

Figure 1.6 The Systematic Approach to Design model of the design process (adapted from Pahl and Beitz [45])

4. Detail Design

These are covered in more detail in the following paragraphs.

Clarification of the Task

This is an analytical phase where the design problem is explored to ensure that the problem is fully understood. Information is researched and collected to identify the requirements and constraints imposed upon the design solution; these are written into performance specifications that the final design must embody and satisfy. Prototypes are used to further the designers' understanding of the problem [49].

[49] Dow, S et al. (2011) *The effect of parallel prototyping on design performance, learning, and self-efficacy*

Conceptual Design

In the conceptual design phase, the key problems are first identified to inform the main functions required. Different solution principles are investigated and then combined into concept designs. These design concepts are evaluated against the performance specification and contrasted against each other to select a design to develop further. In this phase, *proof–of–concept* prototypes are typically used to generate and explore different designs. Frequently, concepts are explored in parallel and iterated multiple times as the designs develop to ensure that the requirements are met [18].

Embodiment Design

During the embodiment design phase, the layout and form of the design are developed in more detail – adding more information to the design concepts. As aspects of the design are clarified, they are evaluated against performance, technical and economic criteria. *Proof–of–product* prototypes are used in this phase to develop the design and test against the criteria.

Detail Design

The form, functional properties, materials, and manufacturing processes are finalised, with the optimisation of the design playing a key part. The last task is to produce the technical drawings and documents required for manufacturing. Depending on the extent of the detail design, both *proof–of–process* and *proof–of–production* prototypes are used to ensure the design meets product requirements and viability of manufacture. These are also known as *integration* or *milestone* prototypes (see Section 2.2.1).

Process Objectives for Prototyping

The *prescriptive* models of the design process focus on the inputs/outputs at each stage – rather than the design activities to be undertaken. Consequently, the emphasis is on the state of the design solution and how it can be progressed through the design process.

This progression is reliant on the exploration, refinement, learning and communication that prototypes provide [30]. However, this progression is highly iterative [35], and so small differences in cost or time can compound over the course of the product's design iterations. Therefore, a key objective of prototyping is to acquire sufficient information to move forward in product development with minimal expenditure of time and cost.

Therefore the two main objectives in the prototyping process are to minimise the time and cost required to create a prototype iteration. These objectives are:

- *Reduce cost* – aim to reduce resource use, choose cheaper materials, reuse or modify prototypes where possible.
- *Reduce time* – reduce the time required to fabricate prototypes.

The concepts of prototype time and cost are explored further in Section 2.4.

[18] Camburn, B. et al. (2015) *A Systematic Method for Design Prototyping*
[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*
[35] Wynn, D. C. and Eckert, C. M. (2017) *Perspectives on iteration in design and development*

1.4 Improving the Design Process

Due to its importance in new product development – and therefore success of a product, there has been significant research into measuring the design process and the ways the process and the outcomes can be improved. These efforts have taken many forms; from developing new models of the design process and design methodologies [12], through encouraging creativity and innovation [50], to creating novel ways of representing designs and prototyping ideas [15]. Throughout all of these, the driving factors are to reduce development costs, decrease time to market, and increase product quality [25].

The focus on cost, time and quality has led to organisational changes within design companies from *operating in sequence* (i.e. 'Toss the design over the wall' approaches) to *concurrent engineering* with transdisciplinary teams working in parallel [19]. This has brought improvements in preventing costly late–stage changes, reducing development times, and lowering costs [51].

One of the more established approaches to improving the design process is through models that prescribe the requirements at each stage in the design process. These *prescriptive* models (see Section 1.3.2) aim to improve the ways in which designers approach and negotiate the design process by offering a more algorithmic procedure to follow, and are often regarded as providing a particular design methodology [32].

Another approach is through the development and creation of design tools that support the design activities performed in the design process. Within these design tools, prototyping is one of the most critical to the success of the design process [30]. The recent paradigm shift has been towards digital and computational prototyping tools that allow the affordable, rapid manufacture of one–off designs with 3D printing [52] or immersion into simulated designs with virtual reality (VR) [53]. However, there has also been significant research into established prototyping methods: such as sketching and Computer Aided Design (CAD) [42].

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[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[50] Onarheim, B. and Biskjaer, M. M. (2014) *Balancing Constraints and the Sweet Spot as Coming Topics for Creativity Research*
[15] Das, A. K. (2004) *CAD and rapid prototyping as an alternative of conventional design studio*
[25] Ullman, D. G. (2003) *The Mechanical Design Process*
[19] Otto, K. and Wood, K. (2001) *Product Design: Techniques in Reverse Engineering and New Product Development*
[51] Roemer, T. and Ahmadi, R. (2004) *Development Concurrent Crashing and Overlapping in Product Development*
[32] Cross, N. (2008) *Engineering Design Methods*
[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*
[52] Sass, L. and Oxman, R. (2006) *Materializing design: The implications of rapid prototyping in digital design*
[53] Feeman, S. M. et al. (2018) *Exploration and evaluation of CAD modeling in virtual reality*
[42] Shih, Y. T. et al. (2017) *Using suitable design media appropriately: Understanding how designers interact with sketching and CAD modelling in design processes*

1.4.1 Improving Prototyping Tools

Designers use various prototyping tools through out the design process to support their decision making and to develop their understanding of the design space and potential solutions. Jang and Schunn [41] state that it is unlikely that there can be a single tool or artefact that strongly supports design processes from start to end. This is due to the fact that each tool has affordances and limitations that support or hinder the designer at different stages in the design process.

Consequently, many different prototyping tools have been developed to support designers throughout the stages of the design process. Figure 1.7 shows some examples of different prototyping tools. Some of these are more generic (e.g. communication tools or sketching), while others are more domain specific (e.g. CAD or architectural foam models). For example, sketching affords designers fast exploration of ideas with accessible tools, however it lacks the tangibility and detail required later in the design process [42]. Conversely, 3D printing allows the creation of complex geometries at low cost, however it is slow and cannot be easily modified once printed [54]. These are just two examples, more prototyping tools that are commonly found in the design process are described and evaluated in detail in Section 2.3.

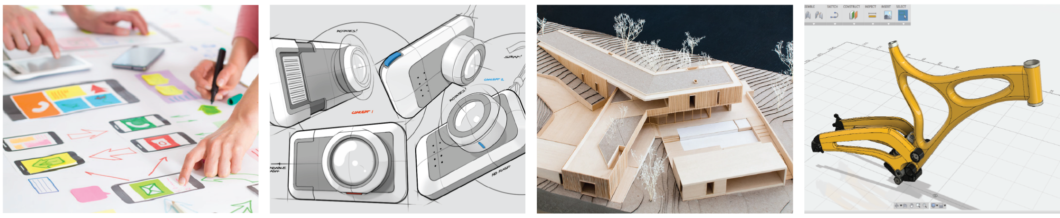

Figure 1.7 Examples of different prototyping tools

Due to their ubiquity, prototyping tools are a common area where developments could bring benefits and improvements to the design process – with a focus on the cost of product development, time to market and quality of product. The elements of time–cost–quality in prototyping are explored and discussed in Section 2.4.

By investigating how prototypes are used and their affect on designers and the design process, prototyping can better understood in the design process. This could allow prototyping to be more effectively implemented in the design process. At the core, designers have to choose from a vast array of prototyping methods, while balancing the resources and time associated with prototyping against the necessity and usefulness of their output. The conflicting demands on prototyping can be addressed to improve the design process. The research areas can be broadly split into two areas:

- Deeper understanding of prototyping principles and tools can lead to systematic

[41] Jang, J. and Schunn, C. D. (2012) *Physical Design Tools Support and Hinder Innovative Engineering Design*
[42] Shih, Y. T. et al. (2017) *Using suitable design media appropriately: Understanding how designers interact with sketching and CAD modelling in design processes*
[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*

prototyping frameworks that dictate when and how prototypes are used in the design process [18].
- Technological advancements of prototyping tools – e.g. improvements in additive manufacturing affording the fabrication of complex parts at a fraction of the cost of traditional manufacturing processes [52].

These two research areas are addressed and discussed in more depth in Section 2.4.

1.5 Thesis Aim

Prototyping can be viewed as playing a dichotomous role in the design process. Its inclusion helps develop the design solution, improves the designer's understanding, and communication with stakeholders, but at the same time increases the resource costs and slows down iterations as prototypes take time to be designed, built and tested. It follows that there is scope to improve prototyping – to either increase its benefit to the design process or reduce the limitations of its use.

Most attempts at improving prototyping have focussed on improving the prototyping process. These efforts create heuristic prototyping framework guides that help direct the prototyping strategies and efforts [11], [12], [55] – i.e. what methods to employ, when to apply them and how best to use them. These approaches look at maximising the benefit from using existing prototyping tools and managing the prototyping process in the design process.

However, the two biggest factors hindering the use of prototypes earlier and more frequently in the design process are the cost and the time required to produce them [18], [19]. However, there is no single technique that affords rapid and cheap fabrication of prototypes at suitable levels of fidelity, while supporting all the objectives of prototyping [12], [41]. Therefore, the motivation of this thesis is to address this gap in research. The general aim of the thesis is to improve prototyping techniques in the early stages of the design process by reducing costs and fabrication times, while maintaining appropriate fidelity. This will focus on how the prototyping technologies themselves can be developed and their use leveraged to address these issues.

This general aim directs the literature search and contextualises the findings from existing research in the field of prototyping. The Design Research Methodology (DRM) is used

[18] Camburn, B. et al. (2015) *A Systematic Method for Design Prototyping*
[52] Sass, L. and Oxman, R. (2006) *Materializing design: The implications of rapid prototyping in digital design*
[11] Menold, J. et al. (2017) *Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[55] Christie, E. J. et al. (2012) *Prototyping Strategies : Literature Review and Identification of Critical Variables*
[19] Otto, K. and Wood, K. (2001) *Product Design: Techniques in Reverse Engineering and New Product Development*
[41] Jang, J. and Schunn, C. D. (2012) *Physical Design Tools Support and Hinder Innovative Engineering Design*

to guide the overall methodology of this thesis. As a result, the following two chapters (Chapters 2 and 3) form part of the *task clarification* to understand the research challenges. After an extensive literature review and preliminary study into early stage prototyping, the specific aim and objectives for the thesis are presented in Chapter 4. The full thesis structure is set out in the following section.

1.5.1 Thesis Structure

Figure 1.8 shows the structure of the thesis with a brief summary of each chapter. Following this introductory chapter, Chapter 2 provides a literature review of prototyping in the context of the design process, and classifies and evaluates current prototyping methods. The chapter finishes by exploring areas for improvement and identifies a gap in the knowledge. Chapter 3 describes a participant based study that compares different prototyping techniques in a common design task. This study expands on the work first reported by the author at the Design Conference 2018 [4]. From the findings, the concept of Hybrid Prototyping is introduced and the reasons for selecting 3D printing and LEGO are discussed.

At this point, Chapter 4 sets out the specific thesis aim and research questions. The methodological approach this research follows and the technological platform used are described. The chapter finishes with the research plan.

Chapter 5 answers the first research question by establishing the algorithms for creating the Hybrid Prototyping tool and then the potential benefits are simulated with the findings discussed. The study described in this chapter is adapted from a paper first reported by the author in Design Studies, Vol. 62 [1].

Chapter 6 answers the second research question through the development of Design for Fabrication and Assembly (DfFA) rules, and their implementation in case study objects. The development of the rules builds upon a paper first published by the author at 22nd International Conference on Engineering Design (ICED 19), Delft, Netherlands [3].

Chapter 7 answers the third research question. The chapter considers different strategies to maximising the results found in Chapter 6. Three of these are chosen for further investigation, and the results are presented, with the key findings highlighted.

Chapter 8 describes the overall HP methodology, the functionality and workflow of the digital tool, and how it can be used to achieve particular prototyping goals. This chapter brings together the preceding three chapters and applies the Hybrid Prototyping methodology to the development of a real–world product. The results are presented and the findings discussion.

[4] Mathias, D. et al. (2018) *Characterizing the Affordances and Limitations of Common Prototyping Techniques to Support the Early Stages of Product Development*

[1] Mathias, D. et al. (2019) *Accelerating product prototyping through hybrid methods: Coupling 3D printing and LEGO*

[3] Mathias, D. et al. (2019) *Hybrid Prototyping: Pure Theory or a Practical Solution to Accelerating Prototyping Tasks?*

The fulfilment of the aim, research questions and how they have been answered are discussed in Chapter 9. This includes reporting the key findings (and limitations) of the research and considers how it can be applied more generally to other techniques, products, and stages in the design process. Avenues for future work are posited with potential research questions to investigate.

The thesis concludes with Chapter 10, which summarises the thesis and demonstrates the author's contribution to knowledge in the field of engineering design and prototyping.

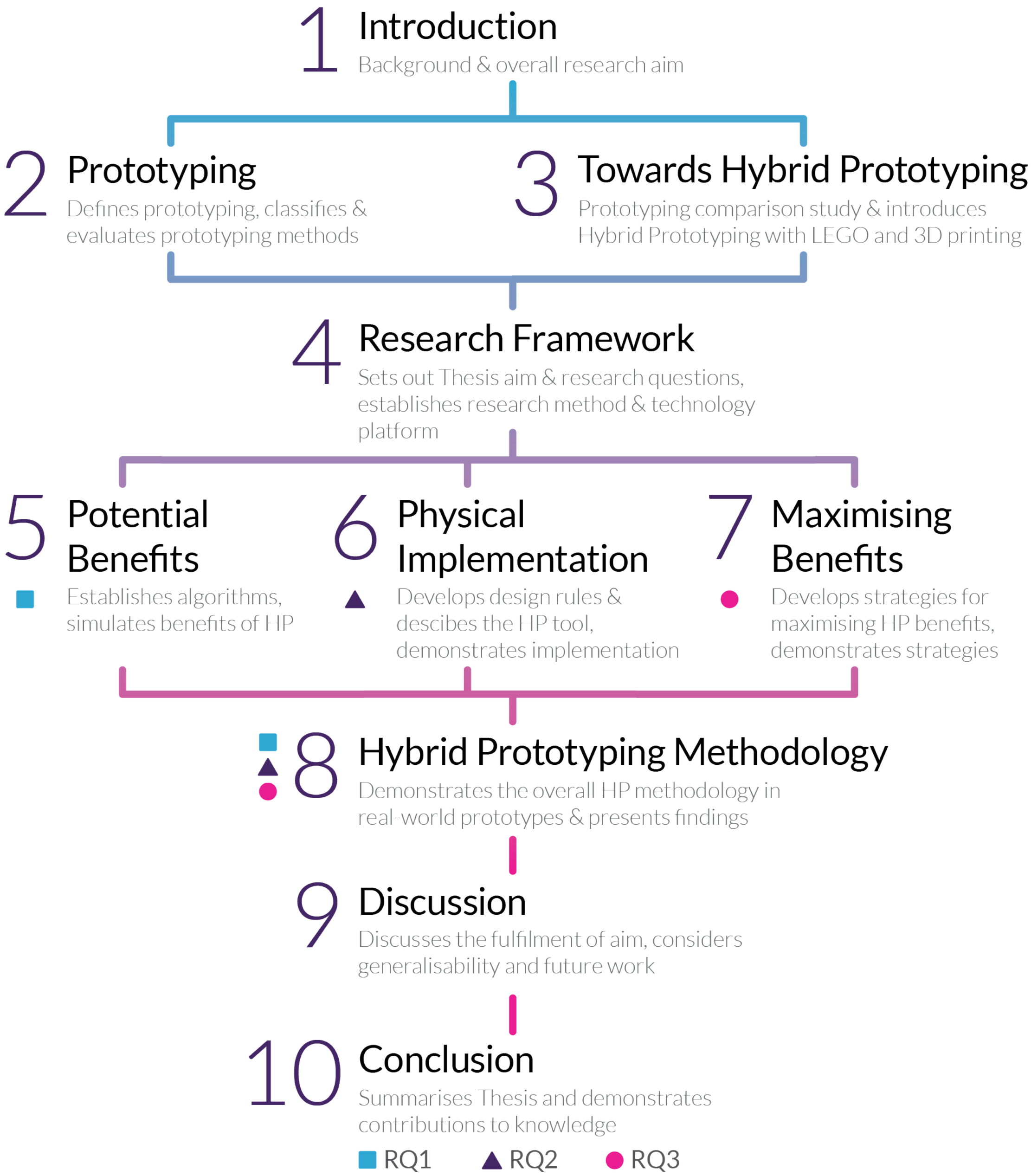

Figure 1.8 The structure and chapter break down of the thesis

Chapter 2

Prototyping

2.1 Overview

This chapter reports a review of the existing prototyping research literature, guided by the general aim of the thesis stated in Chapter 1. The aim of this chapter is to identify the gaps in understanding of prototyping improvements that could be addressed by the research in this thesis. A key part of this is to discuss previous approaches in literature to improving prototyping and prototyping techniques.

The chapter starts by considering how prototyping is defined before continuing to discuss the purpose of prototyping in the design process. Building on this, different approaches to classifying prototypes are drawn from literature and compared. Next, common prototyping techniques are described along with their relative strengths and weaknesses – giving context to the classifications of prototypes. The penultimate section examines the different approaches that have been taken to improve prototyping, with the potential avenues for further research efforts identified. The chapter concludes by outlining the gap in understanding.

2.2 Defining Prototyping

Wall *et al.* [9] state that prototyping is one of the most critical activities in new product development; helping designers progress to a finalized product. Prototyping reduces design risk as it allows designers to develop designs without committing to full production [56]. Prototypes allow designers to understand, test, and develop their ideas and they inform important design decisions throughout the design process. It is widely accepted that increased prototyping has benefits for individual designers and design teams [10], and leads to improved products and a more successful product development process [11], [57].

Yet despite its criticality to the design process, there does not seem to be an overarching definition of a prototype [27]. With the definitions being domain and industry dependent: differing between architecture, software, and engineering [58]. Even perceptions of the breadth and use of prototypes vary between engineering students and professionals [59]. However, a common definition considers prototyping as the act of creating and using prototypes in the design process. Prototypes are frequently considered to be the physical embodiment of a design that allows designers to test its performance against design specifications. This concept of a prototype as a design artefact is reflected by Otto and

[9] Wall, M. B. et al. (1992) *Evaluating prototyping technologies for product design*
[56] Houde, S. and Hill, C. (1997) *What do prototypes prototype?*
[10] Gerber, E. (2009) *Prototyping: Facing uncertainty through small wins*
[11] Menold, J. et al. (2017) *Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design*
[57] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[27] Jensen, L. S. et al. (2016) *Prototypes in engineering design: definitions and strategies*
[58] Beaudouin-Lafon, M and Mackay, W. E. (2007) *Prototyping Tools and Techniques*
[59] Lauff, C. et al. (2017) *Perceptions of Prototypes: Pilot Study Comparing Students and Professionals*

Wood [19], who define a prototype as:

> "a physical instantiation of a product, meant to help resolve one or more issues during the product development."

However, Ulrich and Eppinger [30] consider prototypes to extend beyond a physical artefact to include less tangible approaches to prototyping, such as analytical or virtual prototypes. As shown by their definition:

> "an approximation of the product along one or more dimensions of interest."

Both these definitions only regard the output of prototyping as providing value to the design process, yet the act of prototyping is more than just the creation of a design representation to be measured or evaluated. At a high level, prototyping activities help designers answer questions about their designs while simultaneously giving rise to new ones [24]. Prototyping can support a wide variety of design behaviours, examples include: idea generation, development of knowledge about the design space, and communication between design teams and clients. Camere and Bordegoni [29] expand the definition of prototyping to incorporate the act and outcome. Their definition is:

> "the activity of engaging with the product–to–be, instantiating the design process."

This reflects the importance of prototyping activities within the design process, arguing that the design process cannot exist without prototyping.

For the purposes of this thesis, prototyping (and prototypes) are considered to be both a design activity and a design artefact that help progress the design process. This permits potential approaches to improving prototyping to be viewed through both lens of activity and artefact.

2.2.1 Purpose of Prototyping

The purpose of a prototype is commonly overlooked [60], when in fact, a clear understanding of why a prototype is being used can focus knowledge acquisition and improve the efficiency of the design process. According to Jensen *et al.* [27], a prototype can have two fundamental purposes:

- A *divergent* tool for ideation and synthesis that allows the designer to explore the design space and embody their concepts.
- A *convergent* tool for evaluation and selection that allows the designer to test their design against specifications and requirements.

[19] Otto, K. and Wood, K. (2001) *Product Design: Techniques in Reverse Engineering and New Product Development*
[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*
[24] Yang, M. C. (2005) *A study of prototypes, design activity, and design outcome*
[29] Camere, S. and Bordegoni, M. (2016) *A lens on future products: An expanded notion of prototyping practice*
[60] Schneider, K. (1996) *Prototypes as assets, not toys. Why and how to extract knowledge from prototypes. (Experience report)*
[27] Jensen, L. S. et al. (2016) *Prototypes in engineering design: definitions and strategies*

This aligns with Lim *et al.* [61] who discuss prototypes as *filters*, for exploring new solutions and revealing certain aspects of an incomplete design idea (divergent & creative), and as *manifestations*, that externalise a design idea for communication and evaluation (convergent & evaluative).

While the prototypes themselves can have individual purposes, other authors have described the motivations behind prototyping activities. Menold *et al.* [11] identify three purposes of prototyping; to encourage learning during subsystem design; to act as decision variables in the product development process; and, to enable richer discussions between designers and end users. Similarly, Ulrich and Eppinger [30] propose the following four purposes for prototyping in the design process:

- Learning
- Communication
- Integration
- Milestones

Learning

Prototyping can be used as a learning tool to identify unknowns during the design process. This can include learning about the design problem [49], and exploring potential solutions in the design space [24]. As well as learning about the desirability, viability and feasibility of a design through more focused experimentation [62]. Furthermore, Kiriyama and Yamamoto [63] found that the process of creating a prototype can also give rise to unexpected phenomena that could not have been discovered through discussion or thought alone.

Henderson [64] states that tacit knowledge is gained when prototyping – typically about the technical aspects of the design. This knowledge is embodied in the time taken to plan, build, test, and iterate on the prototypes, which can be difficult to learn through other means.

Overall, learning from the creation and development of prototypes is not limited to specific design phases and is frequently used as a learning tool throughout the design process [45].

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[61] Lim, Y.-K. et al. (2008) *The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas*
[11] Menold, J. et al. (2017) *Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design*
[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*
[49] Dow, S et al. (2011) *The effect of parallel prototyping on design performance, learning, and self-efficacy*
[24] Yang, M. C. (2005) *A study of prototypes, design activity, and design outcome*
[62] Menold, J. et al. (2016) *The Prototype for X (PFX) Framework: Assessing the Impact of PFX on Desirability, Feasibility, and Viability of End Designs*
[63] Kiriyama, T and Yamamoto, T. (1998) *Strategic knowledge acquisition: A case study of learning through prototyping*
[64] Henderson, K. (1995) *The Political Career of a Prototype - Visual Representation in Design Engineering*
[45] Pahl, G. and Beitz, W. (1984) *Engineering Design*

Communication

The development of a new product rarely involves one person in isolation but rather a team of people with a wide range of roles and abilities. Communication and a shared understanding of the project between designers and design teams is crucial for the success of the product [65]. Donati and Vignoli [66] state that the

> "only way to create a shared understanding of an idea in the design process is to convert it into a prototype"

Prototypes facilitate communication as they act as a boundary object between designers' internal mental models and are a shared medium that conveys design intent [28], [36].

Communication is not just required within design teams, but also between project managers, clients, stakeholders, and investors. Prototyping translates technical design language into a communal, tangible representation that enriches the dialogue [67]. As, the design firm, IDEO's Kelley [68] says

> "Good prototypes don't just communicate – they persuade."

A key part of a prototype's ability to communicate design ideas is its level of fidelity. This is discussed further in Section 2.2.2, however the quality and fidelity of prototypes can affect how stakeholders perceived and interpreted the designs [69], [70].

Integration

Integration prototypes are used to check the assembly of components and subsystems and ensure that they function together as a complete design [30]. Physical prototypes are the most effective at integrating parts of a design as it affords the physical interconnections of the constituent parts. During this process, the overall function of the design can be verified and any problems identified.

Milestones

Prototyping for milestones is typically done in the later stages of the design process [30] and is used to demonstrate the capability of the product and how that compares with the performance requirements. These prototypes are frequently used as stage-gates in the design process, that are a 'must pass' before the process can continue. More commonly, milestone prototypes are known as *Alpha*, *Beta*, or *Pre–production* prototypes.

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[65] Bucciarelli, L. L. (2002) *Between thought and object in engineering design*
[66] Donati, C. and Vignoli, M. (2015) *How tangible is your prototype? Designing the user and expert interaction*
[28] Boujut, J.-F. and Blanco, E. (2003) *Intermediary Objects as a mean to foster Co-operation*
[36] Carlile, P. R. (2002) *A Pragmatic View of Knowledge and Boundaries: Boundary Objects in New Product Development*
[67] Bogers, M. and Horst, W. (2014) *Collaborative prototyping: Cross-fertilization of knowledge in prototype-driven problem solving*
[68] Kelley, T. (2001) *Prototyping is the Shorthand of Design of innovation*
[69] Sauer, J. and Sonderegger, A. (2009) *The influence of prototype fidelity and aesthetics of design in usability tests: Effects on user behaviour, subjective evaluation and emotion*
[70] Jensen, L. S. et al. (2018) *Prototyping in Mechatronic Product Development: How Prototype Fidelity Levels Affect User Design Input*
[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*

As this thesis is focussed on the early stages of the design process, the key purposes of prototyping are to *learn* about the design and *communicate* it to stakeholders. *Integration* and *milestone* purposes are more relevant in the later stages of the design process. Consequently, the remainder of literature review does not consider *integration* or *milestone* prototypes when discussing prototyping techniques or methods to improve prototyping.

2.2.2 Classifying Prototypes

The drive to classify prototypes allows designers to understand their capabilities and potential uses, and, as a result, their impact and effectiveness in the design process. This shared understanding of prototypes can reduce the complexities in their selection, fabrication and use. In literature, this classification has typically been applied heuristically to example cases from industry or student studies. However, in order to describe prototypes more generally, several taxonomies have been written that classify prototypes based on their different dimensions [60], [71], [72].

One of the seminal works on classifying prototypes was the model developed by Houde and Hill [56]. They offer a model for classifying prototypes based on three dimensions where a prototype can be described by the proportion of these it employs;

1. *Role* – The functionality of the design and its capability to solve the design problem.
2. *Look and Feel* – The appearance and user experience of the design.
3. *Implementation* – The technical feasibility of how the design will work.

Figure 2.1 shows the model with the three dimensions at the corners of the triangle. There is a further fourth type, *integration* prototypes, which combine all the dimensions into a comprehensive prototype that closely matches all the aspects of the final design. However, these prototypes are used later in the design process and out of scope of the thesis. Parallels can be drawn from Houde and Hill's model in Buchenau and Sura's classifications of *behaves–like* (Role), *looks–like* (Look and Feel), and *works–like* (Implementation) prototypes [31].

Another useful classification is described by Ulrich and Eppinger [30], their model uses two dimensions to characterise prototypes:

1. The *embodiment* of the prototype – the degree to which a prototype is *physical* as opposed to *virtual*.
2. The *scope* of the prototype – the degree to which a prototype is *comprehensive* as opposed to *focussed*.

[60] Schneider, K. (1996) *Prototypes as assets, not toys. Why and how to extract knowledge from prototypes. (Experience report)*
[71] Pei, E. et al. (2011) *A taxonomic classification of visual design representations used by industrial designers and engineering designers*
[72] Hannah, R. et al. (2008) *A Proposed Taxonomy for Physical Prototypes: Structure and Validation*
[56] Houde, S. and Hill, C. (1997) *What do prototypes prototype?*
[31] Buchenau, M. and Suri, J. (2000) *Experience Prototyping*
[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*

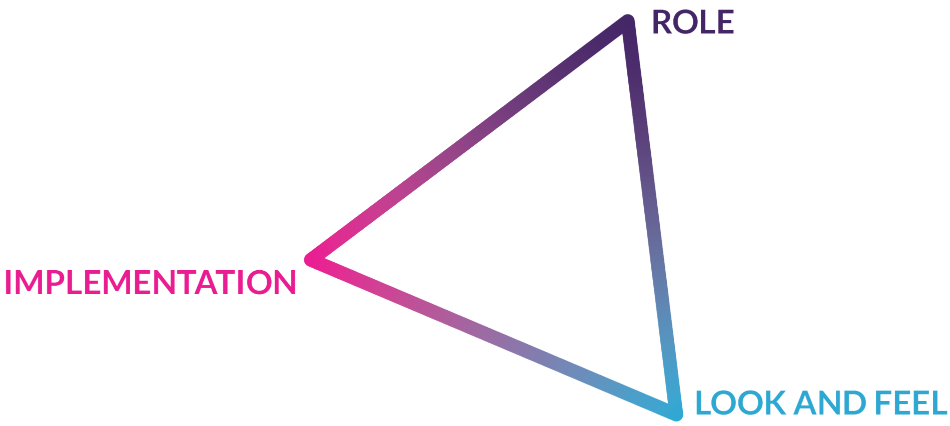


Figure 2.1 Houde and Hill's [56] classification model of prototypes, showing the three dimensions at the corners of the triangle

Figure 2.2 shows both these dimensions on orthogonal axes and results in four general quadrants of prototypes. *Virtual–Focussed* prototypes are typically mathematical or analytical models that describe a small element of the design's functionality but also cover visual representations of the design, while *Physical–Focussed* include physical tests of isolated components, as well as mock-ups of the design's overall form. Generally in the design of physical products, *Virtual–Comprehensive* prototypes are not feasible as it is too complex to fully model the complete functionality – however they are more common in software design. *Physical–Comprehensive* prototypes are the fully integrated version of the whole design that look and function like the final design. These are usually employed later in the design process when the solution is more complete (see Section 2.2.1 and Section 2.2.1). Consequentially, more *comprehensive* prototypes are beyond the scope of the thesis.

Other authors have identified more dimensions that distinguish different types of prototypes. Jensen *et al.* [73] state that these characteristics can loosely by described by six themes: the *material* the prototype is made from, its level of *interactivity* with the user, its *visual detail*, the *purpose* of the prototype, the contextual *surroundings* outside of the designer's control, and the *technology* required to produce the prototype. However, these themes appear incomplete, as the list does not include the prototype's functionality or the point at which it is used in the design process – two dimensions that appear in literature. From a literature overview, Blomkvist and Holmlid [74] created a prototype framework that consisted of six perspectives: *purpose*, *fidelity*, *audience*, *position in the process*, *technique*, and *representation*. While Sauer and Sonderegger [69] offer four dimensions: degree of *functionality*, similarity of *interaction*, breadth of *features*, and *aesthetic* refinement.

The subsequent sections provide five general, domain independent dimensions that have been drawn from literature. As previously described in Chapter 1, prototyping is

[73] Jensen, M. et al. (2015) *Measuring Prototypes - a standardized quantitative description of prototypes and their outcome for data collection and analysis*
[74] Blomkvist, J. and Holmlid, S. (2011) *Existing Prototyping Perspectives: Considerations for Service Design*
[69] Sauer, J. and Sonderegger, A. (2009) *The influence of prototype fidelity and aesthetics of design in usability tests: Effects on user behaviour, subjective evaluation and emotion*

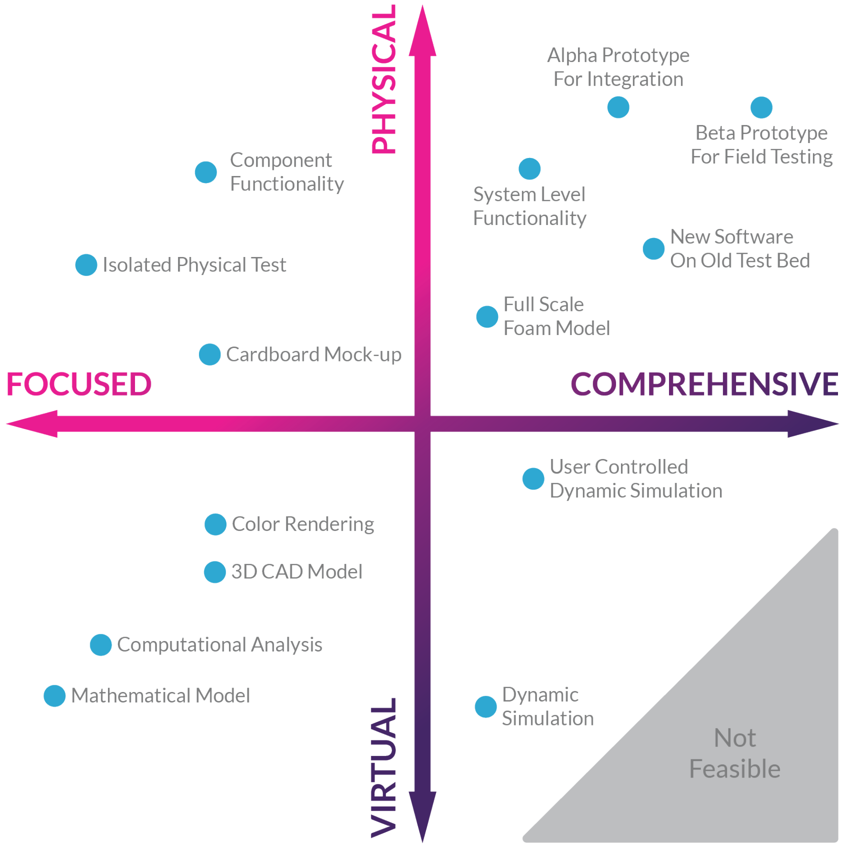


Figure 2.2 Classification of prototypes along two dimensions: the degree they are physical and the proportion of the design's functionality implemented (adapted from Ulrich and Eppinger [30])

used throughout all stages of the design process. However, these dimensions are viewed through the lens of prototyping in the early stages of the design process to fit within the scope of this thesis. Table 2.1 outlines and summarises the five dimensions.

Table 2.1 Five dimensions for classifying prototypes

Dimension	Summary
Purpose & Audience	What and who is the prototype for?
Embodiment	What tool is used to create the prototype?
Scope	How much of the design is being prototyped?
Functionality	What level of functionality does the prototype have?
Fidelity	What is the resolution and precision of the prototype?

Purpose & Audience

The purpose and intended audience of a prototype is tightly coupled with the other characteristics identified in literature, as these factors tend to dictate the embodiment, scope, functionality, and fidelity required. As a result, this could be considered as the top-level characteristic by which all prototypes can be classified. The general purposes of prototyping are discussed in Section 2.2.1 and so it is clear to see how prototypes could be classified by their purpose – a prototype for exploring the design space (i.e. Learning, see Section 2.2.1) is different to one used to communicate the design to a stakeholder (i.e. Communication, see Section 2.2.1). However, this difference is not without subjectivity, as frequently, a single prototype instance could have many purposes and act as a both a learning and communication tool. For example, a cardboard mock-up of a new medical-device could not only be a way to share a design idea with other members of the design team, but also be a learning tool for the designer to understand the ergonomics of their concept. Correspondingly, a key decision when determining the purpose of a prototype is who the intended audience is, whether it is internally within the design team or company, or externally with clients or customers [75]. Internal prototypes tend to be less polished and exist only for the benefit of the designer and the team, while external ones need to be more refined and have high production quality, with an almost performative nature, to impress clients [76].

Embodiment

One property that prototypes are frequently and easily characterised by is the embodiment of the design [77]. This describes what form the prototype takes - from simple sketches or computational models to cardboard mockups and detailed foam models, or even virtual reality simulations of the product. Ulrich and Eppinger [30] define this as *virtual* versus *physical* prototypes. Mathias *et al.* [4] take this further and classify prototypes by four categories: *paper-based* (e.g. sketching), *computer-based* (e.g. CAD), *constrained* physical (e.g. construction kits), and *free-form* physical (e.g. foam modelling). As a result, the embodiment of a prototype manifests itself as the technique or representation used by the designer to fabricate the design [61]. The technique can include the materials and fabrication approach [44] or the tools and methods employed [74]. For a more exhaustive list, Section 2.3 covers the current prototyping techniques.

Ultimately, it is the designer's decision how to embody the design to match the prototype's purpose and audience. Furthermore, the choice of technique to realise their design is dependent on the skill and experience of the designer – Viswanathan *et al.* [78] state that designers must have sufficient skills in creating prototypes in order to leverage and maximise the benefits of the prototyping instance.

Scope

The scope of a prototype is the proportion of features of the final product that are tested or embodied in the prototype. It can be understood as the level of inclusiveness – whether

[75] Bryan-Kinns, N. and Hamilton, F. (2002) *One for All and All for One: Case Studies of Using Prototypes in Commercial Projects*
[76] Crilly, N. et al. (2004) *Seeing things: consumer response to the visual domain in product design*
[77] Camburn, B. et al. (2013) *Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment*
[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*
[4] Mathias, D. et al. (2018) *Characterizing the Affordances and Limitations of Common Prototyping Techniques to Support the Early Stages of Product Development*
[61] Lim, Y.-K. et al. (2008) *The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas*
[44] Hallgrimsson, B. (2012) *Prototyping and Modelmaking for Product Design*
[78] Viswanathan, V. et al. (2015) *Prototyping: A key skill for innovation and life-long learning*

the prototype covers one or several features of the design idea. Ulrich and Eppinger [30] introduced the concept of scope by contrasting *focussed* and *comprehensive* prototypes as one of their key dimensions of prototyping. Similarly, McCurdy *et al.* [79] considered the scope of a prototype by suggesting that the *depth* of functionality and *breadth* of functionality should be assessed separately; creating granularity and characterisation between deep (focussed) and broad (comprehensive) prototypes.

The scope must be tightly matched to the purpose of the prototypes, because if the scope is broader than required, resources, time and effort are wasted in creating superfluous details. In their economic principle of prototyping, Lim *et al.* [61] state:

> "the best prototype is one that, in the simplest and most efficient way, makes the possibilities and limitations of a design idea visible and measurable."

Functionality

A prototype's functionality is how closely its capability, operation, and behaviour match that of the final design – i.e. the *form* versus *function* of a prototype [71]. This falls into the *works like*, *looks like*, *behaves like* classification posited by Buchenau and Suri [31] and Hallgrimsson [44]. Form prototypes are used to show the visual representation of the design with limited or no functionality, examples include sketch renderings of the product or detailed foam models. While functional prototypes demonstrate the functional aspects of the design, for example a LEGO Technic model of a simple mechanism or a finite element analysis of a structural component.

Fidelity

Rudd *et al.* [80] describe how prototypes can be classified into *low* and *high* fidelity categories. McCurdy *et al.* [79] expanded on this to say:

> "the current range of prototyping methodologies are generally described within a spectrum of fidelity."

Although some authors consider fidelity more broadly in order to distinguish prototypes [69], here fidelity is focussed on the resolution and precision of the attributes being prototyped [58]. Conventionally, fidelity refers to the level of visual representation of the design: with a high fidelity representation being closely matched with the final design, and low fidelity being more primitive or abstract. Typically, low fidelity prototypes

[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*
[79] McCurdy, M. et al. (2006) *Breaking the Fidelity Barrier - An Examination of our Current Characterization of Prototypes and an Example of a Mixed-Fidelity Success*
[61] Lim, Y.-K. et al. (2008) *The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas*
[71] Pei, E. et al. (2011) *A taxonomic classification of visual design representations used by industrial designers and engineering designers*
[31] Buchenau, M. and Suri, J. (2000) *Experience Prototyping*
[44] Hallgrimsson, B. (2012) *Prototyping and Modelmaking for Product Design*
[80] Rudd, J. et al. (1996) *Low vs. high-fidelity prototyping debate*
[69] Sauer, J. and Sonderegger, A. (2009) *The influence of prototype fidelity and aesthetics of design in usability tests: Effects on user behaviour, subjective evaluation and emotion*
[58] Beaudouin-Lafon, M and Mackay, W. E. (2007) *Prototyping Tools and Techniques*

(such as sketches or junk models) are low-cost and created quickly to help inform and learn about the design, while high fidelity prototypes (such as highly finished, detailed foam models, or coloured 3D prints) require significant effort to produce and are used to demonstrate and communicate designs. This spectrum of fidelity was investigated in a study comparing levels of fidelity in the design of a padlock, Jensen *et al.* [70] used four levels of fidelity (from low to high): cardboard, laser cut plywood, 3D printed, and machined aluminium.

Generally, the higher the fidelity of the representation, the more skill and time required to create it [44]. Higher fidelity prototypes may force the designer to make additional decisions about design details in order to achieve the desired level of fidelity [81].

Sauer and Sonderegger [69] and Jensen *et al.* [70] found that prototype quality and fidelity played an important role in how stakeholders perceived the design. This phenomenon is not limited to physical prototypes, for example, Macomber and Yang [82] investigated how sketch quality influenced stakeholder feedback and found that realistic and clean sketches were ranked higher than rough sketches. Furthermore, Camburn *et al.* [12] state that higher fidelity representations lead to accurate interpretation of the design. Consequentially, in the design of *user–driven* products, high fidelity prototypes are preferable to elicit useful stakeholder and user feedback on the design. However, low fidelity prototypes are still valuable as they provide a high level design insight to cost/time ratio. And as a result, allow for a larger number of design iterations within the same budget constraints. Consequently, low fidelity prototyping is still ubiquitous in the early stages of the design process.

2.3 Prototyping Techniques

As shown by the range of purposes (see Section 2.2.1) and dimensions for classifying prototypes (see Section 2.2.2), there is a enormous scope for how prototyping manifests in the design process.

As a result, a multitude of prototyping tools and methods are used and have been developed specifically to support prototyping. The choice of technique is dependent on which prototyping objectives (see Section 1.2.1) the designer aims to meet. Frequently, these decisions are managed through the use of prototyping frameworks that guide the

[70] Jensen, L. S. et al. (2018) *Prototyping in Mechatronic Product Development: How Prototype Fidelity Levels Affect User Design Input*
[44] Hallgrimsson, B. (2012) *Prototyping and Modelmaking for Product Design*
[81] Lawson, B. (2002) *CAD and Creativity,: Does the Computer Really Help?*
[69] Sauer, J. and Sonderegger, A. (2009) *The influence of prototype fidelity and aesthetics of design in usability tests: Effects on user behaviour, subjective evaluation and emotion*
[82] Macomber, B. and Yang, M. C. (2011) *The Role of Sketch Finish and Style in User Responses To Early Stage Design Concepts*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*

prototyping efforts [11], [12]. However, given the range and importance of prototypes there exists a significant body of research concerned with the various techniques for prototyping used by designers in industry and education.

The focus of this section will be on prototyping techniques that are used for *learning* and *communication* purposes in the early stages of the design process. Ullman [25] describes these as *Proof–of–Concept* prototypes that help identify what approach to take when designing a new product.

Prototypes used for *integration* and *milestone* purposes are typically more complex assemblies that comprise of many components, materials, and manufacturing processes [30] and are not considered in this thesis.

The following examples give the benefits and limitations of prototyping techniques currently used by designers. The examples are separated into the two categories (virtual and physical) as identified by Ulrich and Eppinger [30]. Table 2.2 summarises the affordances and limitations of the common prototyping techniques.

2.3.1 Virtual Prototyping

Virtual prototyping is well established within engineering design and aims to develop a product using software, computer models, and detailed digital mock-ups to replace the necessity of physical prototypes [83]. Typically, this is employed throughout large engineering projects, such as aircraft, where the scale, cost, and time of integrated physical prototypes make their implementation infeasible.

However in the early stages of the design process, this traditional definition is replaced with one that is more closely associated with Ulrich and Eppinger's [30] dimension of virtual being opposed to physical. Therefore the scope of the virtual prototyping has been expanded to include techniques that are represented visually or mathematically but are intangible – i.e. paper-based prototyping (e.g. sketching), as well as the more conventional computer–based prototyping (e.g. CAD). Aligning with the expanded notion of prototyping posited by Camere and Bordegoni [29] that it is the activity of engaging with the product–to–be.

Sketching

Sketching is frequently used in idea generation activities and embodying preliminary ideas [84]. It is the ubiquitous and traditional tool for exploratory, early stage design

[11] Menold, J. et al. (2017) *Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[25] Ullman, D. G. (2003) *The Mechanical Design Process*
[30] Ulrich, K. T. and Eppinger, S. D. (2016) *Product Design and Development*
[83] Wang, G. (2002) *Definition and Review of Virtual Prototyping*
[29] Camere, S. and Bordegoni, M. (2016) *A lens on future products: An expanded notion of prototyping practice*
[84] Yang, M. C. (2009) *Observations on concept generation and sketching in engineering design*

Table 2.2 Affordances and limitations of common prototyping techniques

Technique	Affordances	Limitations
Sketching	– Low cost – Quick	– Non-tangible – Experience/skill required
Computer Aided Design	– Precise geometry – Ease of modification – Photorealistic	– Non-tangible – Experience/skill required
Virtual Reality	– Immersive – Photorealistic – Sense of depth and scale	– Limited design tools – In its infancy
Junk Modelling	– Quick – Low cost – Tangible – Reusable/modifiable	– Crude representations – Limited use
Construction Kits	– Quick – Low cost – Tangible – Reusable/modifiable – Low skill threshold	– Blocky representations – Constrained construction
Foam/Cardboard Modelling	– Low cost – Organic/complex shapes – Tangible	– Experience/skill required – Slow fabrication times
3D Printing	– Organic/complex shapes – Tangible	– Experience/skill required – Slow print times – Not possible to modify

due to its speed and few tool requirements [85]. Sketching's strength lies in its intuitive interaction and ability to quickly capture and communicate design ideas while preserving ambiguity and design freedom at the fuzzy front end of design [86].

Sketches can range from rough, proverbial back–of–the–envelope drawings to full–colour renders, complete with approximate dimensions and annotations (see Figure 2.3). Yet despite this, the lack of tangibility and depth in a 2D representation is a weakness of sketching and Shih *et al.* [42] state that:

> "2D sketches may not convey ideas about complicated 3D objects."

This can reduce the effectiveness of using sketches to communicate design ideas with

[85] Faas, D. et al. (2014) *Preliminary Sketching and Prototyping: Comparisions in Exploratory Design-and-build Activities*
[86] Fixson, S. K. and Marion, T. J. (2012) *Back-loading: A potential side effect of employing digital design tools in new product development*
[42] Shih, Y. T. et al. (2017) *Using suitable design media appropriately: Understanding how designers interact with sketching and CAD modelling in design processes*

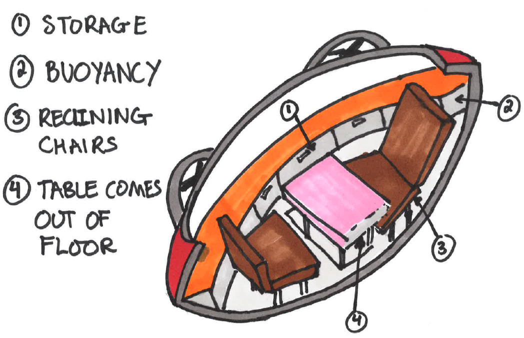


Figure 2.3 An example of an annotated concept sketch

non-technical stakeholders [87]. Furthermore, while the ambiguity and flexibility of sketches is beneficial to designers, it becomes problematic as the concepts develop beyond the divergent stages.

Ambiguous sketches can result in the flow of the design process being interrupted when they are transferred to physical prototypes or 3D digital models – something Ranscombe and Bissett-Johnson [88] have attempted to address with their *digital sketching tool* that bridges the transition from sketching to digital modelling.

Computer Aided Design

Computer aided design (CAD) is considered synonymous with 3D modelling, yet it extends beyond merely creating geometry to include computational simulation and integration with assembly and manufacture. However, in the earlier stages of the design process, CAD can be found in two main forms: digital design tools and analytical computational models [55].

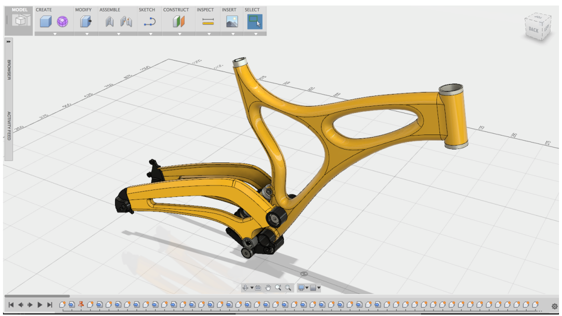


Figure 2.4 An example of a CAD assembly

CAD has become ubiquitous in the design process [81] and improvements in the tools available means that CAD can be used from ideation all the way through to manufacture. Fixson and Marion [86] states that:

[87] Deininger, M. et al. (2017) *Does Prototype Format Influence Stakeholder Design Input?*
[88] Ranscombe, C. and Bissett-Johnson, K. (2017) *Digital Sketch Modelling: Integrating digital sketching as a transition between sketching and CAD in Industrial Design Education*
[55] Christie, E. J. et al. (2012) *Prototyping Strategies : Literature Review and Identification of Critical Variables*
[81] Lawson, B. (2002) *CAD and Creativity,: Does the Computer Really Help?*
[86] Fixson, S. K. and Marion, T. J. (2012) *Back-loading: A potential side effect of employing digital design*

> "almost no product development project is conducted without the use of CAD models."

Primarily, CAD tools permit the creation of editable, parametric 3D models that can be easily modified throughout the design process (see Figure 2.4). CAD affords high precision modelling that allow designers to add dimensionality to initial design concepts. Its strength also lies in being able to create photo–realistic renders of designs, that are a powerful tool in communicating with clients and stakeholders.

Other than being able to leverage computational power, one of the key benefits of CAD is the flexibility and reconfigurability of digital models – i.e. storing multiple variants of a design, ease of transforming/editing designs and undoing mistakes, and the ability to quickly modularise aspects of designs.

From these digital 3D models, it is possible to perform computational simulations. For example, computational fluid dynamics (CFD) can be used to calculate the airflow around a car body, finite element analysis (FEA) can simulate the forces on the design, and tool path generation can determine the manufacturability of a component. These allow designers to test functional aspects (i.e. mechanical stress in load bearing components using FEA) of their designs without having to build and test physical prototypes – helping inform the designer about the behaviour of components to enable quicker design iterations and reducing the time spent creating physical models.

However, Ullman *et al.* [89] found that the use of CAD encouraged a depth–first, rather than breadth–first, approach to the generation of ideas. Fixson and Marion [86] state that the use of CAD can cause an early jump into detail design, effectively shortcutting concept development. Furthermore, design students can fall into the trap of creating high fidelity, 'good looking' representations rather than one that answers the design question at hand [88]. In both cases, the designers become fixated by the tool they are using.

Virtual Reality & Augmented Reality

Despite the precision and photo-realism, CAD prototypes lack a sense of scale, form, and size due to the limitations of the flat, 2D display of the computer. Virtual reality (VR) and augmented reality (AR) begin to address this through the use of a headset with stereo displays. Designers and stakeholders can have an immersive, photo–realistic experience with a digital version of the product (see Figure 2.5) – giving it size and depth, but still lacking true tangibility and physicality.

VR is developing beyond a purely visual environment for communication. Research has been carried out on how the flexibility of sketching and quick exploratory design can be

tools in new product development

[89] Ullman, D. G. et al. (1990) *The importance of drawing in the mechanical design process*

[86] Fixson, S. K. and Marion, T. J. (2012) *Back-loading: A potential side effect of employing digital design tools in new product development*

[88] Ranscombe, C. and Bissett-Johnson, K. (2017) *Digital Sketch Modelling: Integrating digital sketching as a transition between sketching and CAD in Industrial Design Education*

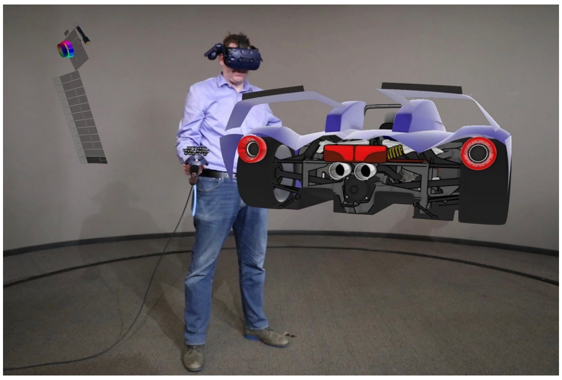


Figure 2.5 An example of immerse interaction in VR

translated into VR [90] but requires significant development before designers can develop the experience and fluency comparable to more established tools such as sketching and CAD.

While the potential use and impact is enormous, the use of AR and VR in the design process is in its infancy and is not considered further in this thesis.

2.3.2 Physical Prototyping

In spite of the enormous inroads digital tools have made, physical prototypes are still an integral part of the design process [15]. Donati and Vignoli [66] states that this is because

> "prototypes that are more tangible facilitate creativity, interaction and communication."

Physical prototypes afford intuitive exploration of the design space. Dow *et al.* [49] showed the developing multiple prototypes in parallel allowed the designers to discover more diverse solutions. Furthermore, Youmans [22] found that physical models reduce design fixation that can be present in virtual methods.

Physical prototypes are also effective communication and collaboration tools. The product design firm IDEO, encourages the use of physical prototypes as they improve communication between people and can help persuade clients [91]. Terwiesch and Loch [92] establish collaborative prototyping tools that include the customer and their input in the prototyping process, allowing both the customer and designer to affect the outcome.

However, the two most significant factors hindering the use of physical prototypes in

[90] Arora, R. et al. (2017) *Experimental Evaluation of Sketching on Surfaces in VR*
[15] Das, A. K. (2004) *CAD and rapid prototyping as an alternative of conventional design studio*
[66] Donati, C. and Vignoli, M. (2015) *How tangible is your prototype? Designing the user and expert interaction*
[49] Dow, S et al. (2011) *The effect of parallel prototyping on design performance, learning, and self-efficacy*
[22] Youmans, R. J. (2011) *The effects of physical prototyping and group work on the reduction of design fixation*
[91] Kelley, T. and Littman, J. (2001) *The Art of Innovation*
[92] Terwiesch, C. and Loch, C. (2004) *Collaborative prototyping and the pricing of custom-designed products*

the design process is the cost and the time required to produce them [18], [19]. This is echoed by Baxter [48] and Ullman [25] who state that as physical models are expensive and time-consuming to produce, the frequency of their use is limited. This is reiterated by Thomke and Bell [93] who observed that companies attempt to lower costs by delaying prototype fabrication as long as possible.

Junk Modelling

The simplest form of physical prototyping is junk modelling. This approach combines existing objects or modifies other products to rough out an overall design or shape. Hallgrimsson [44] talks of design meetings where crude prototypes were quickly fashioned out of items found in the room (e.g. stationery and pieces of paper). Figure 2.6 shows a junk model for a surgical tool.

Figure 2.6 An example of a junk model

Prototypes like these are typically used in the very early design phases where investigating many ideas in quick succession is key to exploring the design space. The impact of the constraints and low effort construction prevents designers getting fixated on creating a detailed design too early in the design process by reducing the role of sunk cost [94].

However, their transience and lack of fidelity limits their usefulness in the process as the design develops.

Construction Kits

Construction kits are a formalised version of junk modelling – employing a library of standard parts with common interfaces. Common examples include LEGO, K'Nex, and Meccano. While these are normally marketed as children's toys, there is a growing trend for construction kits to be used as design tools. The LEGO Group released the LEGO

[18] Camburn, B. et al. (2015) *A Systematic Method for Design Prototyping*
[19] Otto, K. and Wood, K. (2001) *Product Design: Techniques in Reverse Engineering and New Product Development*
[48] Baxter, M. (1996) *Product Design: Practical Methods for the Systematic Development of New Products*
[25] Ullman, D. G. (2003) *The Mechanical Design Process*
[93] Thomke, S. and Bell, D. E. (2001) *Sequential Testing in Product Development*
[44] Hallgrimsson, B. (2012) *Prototyping and Modelmaking for Product Design*
[94] Viswanathan, V and Linsey, J. (2011) *Design Fixation in Physical Modeling: An Investigation on the Role of Sunk Cost*

architecture studio designed as a prototyping tool for architects [95] (see Figure 2.7).

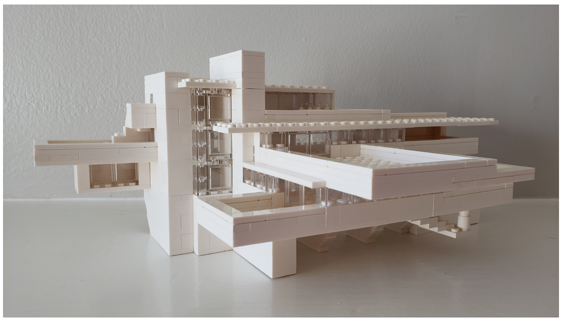


Figure 2.7 An example of a construction kit prototype

The benefits of using construction kits is that they afford fast construction of models and encourage modification and reconfiguration. Furthermore, Garde and Voort [96] claim that LEGO is good tool for co-design as it lowers skill barriers and engages stakeholders. This is echoed by Ranscombe *et al.* [2], who state that LEGO can help educate novice designers in idea fluency.

However, LEGO (and other construction kits) are not without their weaknesses. Boa *et al.* [7] describes the limitations of LEGO and posits ways it could be adapted into a more powerful prototyping tool. These limitations include:

- *Blocky representations* – more organic shapes and swept surfaces are difficult to reproduce in high fidelity with LEGO elements and can therefore only be approximated.
- *Fixed scale* – LEGO's interconnecting stud mechanism fixes the positional resolution at 8mm.
- *Orthogonal construction planes* – due to the placement of studs and their counterpart sockets on opposite sides, LEGO elements can generally only be assembled in one direction.

Cardboard & Foam Modelling

As the design is refined and becomes more concrete, better representations are required to create useful prototypes. The materials typically used are low cost, workable and easily finished – ensuring that the cost and fabrication times of prototypes is reduced. For these reasons, cardboard or expanded foam are frequently used to realise prototypes in the early stages of the design process [13], [44], [97].

With these materials, complex shapes and curves, as well as finer details, can be created that are unachievable with junk modelling or construction kits. Furthermore, combined

[95] The LEGO Group. (2013) *LEGO Architecture Studio*
[96] Garde, J. A. and Voort, M. C. van der. (2016) *Could LEGO ® Serious Play ® be a useful technique for product co-design?*
[2] Ranscombe, C. et al. (2019) *Designing with LEGO: exploring low fidelity visualization as a trigger for student behavior change toward idea fluency*
[7] Boa, D. et al. (2017) *Evolving lego: Prototyping requirements for a customizable construction kit*
[13] James Dyson Foundation. (2010) *Engineering Box - Teacher's Pack*
[44] Hallgrimsson, B. (2012) *Prototyping and Modelmaking for Product Design*
[97] Akaoka, E. et al. (2010) *DisplayObjects: Prototyping Functional Physical Interfaces on 3D Styrofoam, Paper or Cardboard Models*

with painting and decals, high fidelity appearances are feasible. As a result, these techniques are mostly used in *looks–like* prototypes that are used to test overall form and aesthetics of a design, alongside user interaction, ergonomics and stakeholder feedback. It is also possible to create more functional prototypes as cardboard can be structurally strong enough to be used in mechanisms [16].

Figure 2.8 Examples of cardboard and foam prototypes

However, while complex and detailed geometries are possible, they require considerable skill and time in their construction [44].

3D Printing

Additive manufacturing (AM) is the maturation of rapid prototyping, and is more widely know as 3D printing. It is a significant technological step-change in the design process [52], [98], that affords the low-cost fabrication of high fidelity designs with complex geometry and features (see Figure 2.9). While there are several technical implementations of AM, the focus of using it as a prototyping technique is on the low-end filament deposition modelling (FDM) machines where the cost of both the materials and hardware is relatively inexpensive [99]. Conner *et al.* [100] showed that even entry-level 3D printers brought benefits to the design process. While FDM 3D printing is cheaper than traditional manufacturing techniques (e.g. CNC machining), the cost of materials is high compared to the other prototyping techniques such as cardboard or foam modelling [101].

Figure 2.9 An example of a series of 3D printed prototypes

The use of 3D printing as a prototyping technique does require a high level of competency with CAD software or access to an existing library of designs that can be modified

[16] Kim, W.-s. (2009) *Advanced Kinematic Cardboard Prototyping for Robot Development*
[44] Hallgrimsson, B. (2012) *Prototyping and Modelmaking for Product Design*
[52] Sass, L. and Oxman, R. (2006) *Materializing design: The implications of rapid prototyping in digital design*
[98] Campbell, I. et al. (2012) *Additive manufacturing: rapid prototyping comes of age*
[99] Sculpteo. (2016) *The State of 3D Printing*
[100] Conner, B. P. et al. (2015) *An assessment of implementation of entry-level 3D printers from the perspective of small businesses*
[101] Redwood, B. et al. (2017) *The 3D Printing Handbook*

to suit different purposes. However, it does not require experienced practical skills to realise the designs (unlike cardboard or foam modelling), and digital design tools can support and augment the process for creating 3D printed parts [102].

One of the issues with 3D printing is that, once printed, the design is fixed and cannot be easily modified without changing the digital model and reprinting.

2.4 Improving Prototyping

The importance and impact of prototyping in the design process can not be overstated. This, therefore, has lead to significant research efforts to improve the prototyping process, the techniques employed and to develop novel approaches of supporting the design process.

Wall *et al.* [9] identify three dimensions of prototypes that could be improved:

1. *Performance* – the degree of ability for a prototype to fulfil its purpose (e.g. learning or communication).
2. *Unit cost* – the material and equipment costs of a prototype.
3. *Lead time* – the amount of time necessary to fabricate and assemble a prototype.

Prototype *performance* has a broad definition that can include the prototyping activities associated with it. As such, Camburn *et al.* [12] considered four main objectives of prototyping activities (see Section 1.2.1) in their approaches to improving the performance of prototypes. Other researchers have considered how to improve prototyping to better support design activities. Table 2.3 shows authors that have focussed on activity objectives when investigating improving prototype performance.

Table 2.3 The list of authors that investigate improving the activity of prototyping by activity objective

Objective	Authors
Exploration	Menold et al. [11], Camburn et al. [12], Hess and Summers [103], Dunlap et al. [104]
Refinement	Yang [84], Dow [105], Viswanathan and Linsey [21], Dunlap et al. [104]
Active Learning	Menold et al. [11], Viswanathan and Linsey [21], Reid et al. [106],
Communication	Menold et al. [11], Reid et al. [106], Camburn et al. [12]

[102] Goudswaard, M. et al. (2017) *Democratisation of design for functional objects manufactured by fused deposition modelling (FDM): lessons from the design of three everyday artefacts*
[9] Wall, M. B. et al. (1992) *Evaluating prototyping technologies for product design*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[11] Menold, J. et al. (2017) *Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design*
[103] Hess, T. and Summers, J. D. (2013) *Case study: Evidence of prototyping roles in conceptual design*
[104] Dunlap, B. U. et al. (2014) *Heuristics-Based Prototyping Strategy Formation - Development and Testing of*

The second and third dimensions identified by Wall *et al.* [9] are closely linked. Camburn *et al.* [12] include these as corollary process objectives (see Section 1.2.1) as they are critical in defining the prototyping strategy and can limit the scope of the prototyping efforts.

- *Reduce Time* – how can the time to produce a prototype be reduced?
- *Reduce Cost* – how can the cost of a prototype be reduced?

Both of these aspects are typically dictated by the prototyping tools used to create the prototype. The prototype fabrication time is the amount of time required to source, fabricate, assemble, and finish the required prototypes. The fabrication time can include manual craftsmanship (i.e. foam modelling) or automated manufacture (i.e. 3D printing) – this allows fabrication time to be directly compared between different prototyping tools. Most research has focussed on fabrication and assembly (see Section 2.4.2) as these aspects form the majority of the time taken to produce a prototype.

The costs of fabricating prototypes are directly related to the material, equipment, and running costs, the human time cost (i.e. the cost per hour of time for a designer) is not taken into consideration. Typically, designers use the equipment and tools available to them when prototyping [91], and as a result the equipment costs tend to be fixed capital costs that do not affect the cost of a prototype instance. Therefore the reduction in costs can consider ways of using lower cost materials, reducing the material usage or to increased the reusability of prototype (see Section 2.4.2).

As this section has shown, the improvements to prototyping manifest through two main mechanisms: activity improvements, and tool improvements. However, there is a third mechanism that does not fit into the first two – the creation of novel approaches that disrupt the existing prototyping methods and have the potential to cause paradigm shifts in how prototypes are created and used. The following sections consider how improving prototyping can be achieved via these three mechanisms:

- *Activity Improvements* – improving overall prototyping activities in the design process.
- *Tool Improvements* – improving existing prototype fabrication techniques.
- *Disruptive Approaches* – developing novel and disruptive prototyping methods.

2.4.1 Activity Improvements

As previous sections have shown, there is no single prototyping technique that is effective at every stage of the design process. Even in the early stages of the design process,

a New Prototype Planning Tool
[84] Yang, M. C. (2009) *Observations on concept generation and sketching in engineering design*
[105] Dow, S. (2011) *How prototyping practices affect design results*
[21] Viswanathan, V and Linsey, J. (2010) *Physical Models In Idea Generation – Hindrance Or Help*
[106] Reid, T. N. et al. (2013) *Impact of Product Design Representation on Customer Judgment*
[9] Wall, M. B. et al. (1992) *Evaluating prototyping technologies for product design*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[91] Kelley, T. and Littman, J. (2001) *The Art of Innovation*

designers frequently change tools and techniques to match the progression of the design.

Correspondingly, it can be challenging for designers to decide what prototyping approaches to employ, when to apply them and how to get the most benefit [61]. Deininger *et al.* [107] showed that novices employed a very limited number of best practices when using prototypes and that adding intentionality and structure to the process would improve their understanding of prototypes. Otto and Wood [19] stress the importance of timely prototyping efforts and suggest that they should be considered strategically.

As a result, prototyping activity improvements typically manifest as structured frameworks that guide designers on how to implement prototyping in their design activities. Lauff *et al.* [59] state that prototyping frameworks could act as a knowledge transfer tool in design process and could change designers' perception and use of prototypes. Menold *et al.* [11] states that the specifications for a structured prototyping framework should:

- Encourage early and frequent iterative prototyping.
- Enable designers to quickly select prototypes to support decision making.
- Enable engaging prototypes that maximise insight.
- Ensure the appropriateness of prototypes for purpose and audience.

These frameworks are posed as a series of decisions or objectives that dictate what actions will be taken to accomplish the development of the prototypes [55], [104]. For example, Camburn *et al.* [12] split these actions into six individual techniques that can be enacted to meet the different objectives of prototypes: *iterative* prototyping, *parallel* prototyping, *requirement relaxation*, *subsystem isolation*, *scaled* prototyping, and *virtual* prototyping. Table 2.4 shows how these map to meet the requirements of prototyping.

While Menold *et al.* [11] are more general by creating a decision loop for prototyping at any stage (*Prototyping for X*) in the design process. This is organised as *Frame for X*, *Build for X*, and *Test for X*, where *X* is a particular attribute the designer is focussed on. The Frame-Build-Test cycle iterates until insights move the design forward and add to the design knowledge.

Improving prototyping activities in this holistic manner is challenging, and the existing research tends to take a heuristic approach. As a result, it is difficult to generalise these improvements in the prototyping and design of products across different domains and

[61] Lim, Y.-K. et al. (2008) *The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas*
[107] Deininger, M. et al. (2017) *Novice designers' use of prototypes in Engineering Design*
[19] Otto, K. and Wood, K. (2001) *Product Design: Techniques in Reverse Engineering and New Product Development*
[59] Lauff, C. et al. (2017) *Perceptions of Prototypes: Pilot Study Comparing Students and Professionals*
[11] Menold, J. et al. (2017) *Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design*
[55] Christie, E. J. et al. (2012) *Prototyping Strategies : Literature Review and Identification of Critical Variables*
[104] Dunlap, B. U. et al. (2014) *Heuristics-Based Prototyping Strategy Formation - Development and Testing of a New Prototype Planning Tool*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*

Table 2.4 Mapping between improvements and prototype activity and process objectives (from Camburn et al. [12])

Technique	Refinement	Exploration	Communication	Active Learning	Reduce Cost	Reduce Time
Iterative Prototyping	●					
Parallel Prototyping		●				
Requirement Relaxation			●	●	●	●
Subsystem Isolation					●	●
Scaled Prototyping					●	●
Virtual Prototyping			●		●	

industries. However, it is possible to improve prototyping activities through the strategic use and timing of different prototyping techniques within the design process.

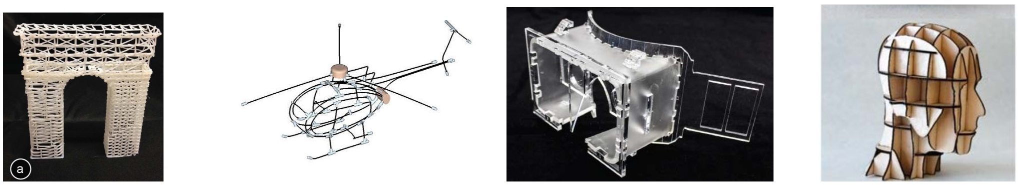
2.4.2 Tool Improvements

Prototyping tool improvements are developments of established prototyping methods and tools to reduce fabrication times, prototype cost, and the complexity and skill requirements of their use.

Several authors have created tools that address fabrication times of prototypes, shown in Figure 2.10. Mueller *et al.* [108] developed *WirePrint* (Figure 2.10a), that speeds up fabrication times on desktop 3D printers by a factor of 10, while simultaneously reducing material usage. This was achieved by generating a sparse wire mesh of the volume that the printer could quickly fabricate. Liu *et al.* [109] followed a similar approach with *WireFab* (Figure 2.10b) that creates a wire skeleton of a design that can be produced by a simple wire bending machine. Beyer *et al.* [110] created *Platener* (Figure 2.10c) that finds planar surfaces of a design and produces sheet files that can be cut on a laser cutter and assembled. Hildebrand *et al.* [111] present *Crdbrd* (Figure 2.10d), a design tool to simplify the creation and assembly of cardboard prototypes. They position it as a low-cost and faster alternative to 3D printing.

Other research has created digital tools that simplify the creation of 3D geometry. Ranscombe and Bissett-Johnson [88] have developed the 'digital sketch' that uses the scaling and manipulation of simple primitives to flesh out designs in a digital environment. This makes the transition from sketching to CAD more seamless and easier to

[108] Mueller, S. et al. (2014) *WirePrint: 3D Printed Previews for Fast Prototyping*
[109] Liu, M. et al. (2017) *WireFab : Mix-Dimensional Modeling and Fabrication for 3D Mesh Models*
[110] Beyer, D. et al. (2015) *Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates*
[111] Hildebrand, K. et al. (2012) *crdbrd: Shape Fabrication by Sliding Planar Slices*
[88] Ranscombe, C. and Bissett-Johnson, K. (2017) *Digital Sketch Modelling: Integrating digital sketching as a transition between sketching and CAD in Industrial Design Education*



(a) WirePrint [108] (b) WireFab [109] (c) Platener [110] (d) Crdbrd [111]

Figure 2.10 Examples of tool improvements to reduce fabrication time

navigate without getting fixated on the detail that is typically required in CAD software. Similarly, the commercial software Adobe Dimension CC [112] permits the rapid creation and rendering of photorealistic product mock ups. Allowing designers to quickly show and evaluate the appearance of the final design. In both cases, the emphasis is on the speed of generating digital designs and useful prototypes that can be used to learn about the design (digital sketching) and communicate with clients (Adobe Dimension CC).

Another approach is to create guides on implementing best practices in different design tools. The LEGO group released the LEGO Architecture Kit [95] that not only provides guidance on how to construct architectural prototypes with LEGO, but also poses questions to the designer to help develop their design thinking. Furthermore, Enjary [113] published an unofficial guide to advance building techniques with LEGO, that pushes the boundaries of what is possible with the construction kit. For 3D printing, design for additive manufacturing (DfAM) guidelines have been developed specifically to support the fabrication of designs using these tools [114], [115]. DfAM instructs best practice for the design of 3D objects when 3D printing – ensuring that the resulting prototypes meet their design requirements [101].

Implementing these tool improvements to reduce prototyping time, cost and complexity could afford the use of prototyping earlier in the design process – encouraging innovation and preventing late stage problems [41]. Reducing the complexity and skill required in using the tools, means that designers can work more quickly and not waste time in creating the representation – further speeding up design iterations.

The key requirement for tool improvements focus on creating a prototype of suitable, if not matching, fidelity that be produced faster and/or more cheaply than the existing tools. While automation and skill reduction feed into this requirement they are not the primary goal in the tool improvement.

[112] Adobe Inc. (2018) *Adobe Dimension CC 2.0*
[95] The LEGO Group. (2013) *LEGO Architecture Studio*
[113] Enjary, D. (2007) *The Unofficial LEGO Advanced Building Techniques Guide*
[114] Goguelin, S. et al. (2016) *A bottom-up design framework for CAD tools to support design for additive manufacturing*
[115] Booth, J. W. et al. (2017) *The Design for Additive Manufacturing Worksheet*
[101] Redwood, B. et al. (2017) *The 3D Printing Handbook*
[41] Jang, J. and Schunn, C. D. (2012) *Physical Design Tools Support and Hinder Innovative Engineering Design*

2.4.3 Disruptive Approaches

Disruptive approaches for improving prototyping consider new ways to prototype in the design process that disrupt the existing methods. Typically, these approaches have not yet become common in the design process but have been posited as potential ways to improve prototyping.

The lack of tangibility in CAD and the constraints of keyboard and mouse, have led researchers to develop tangible user interfaces in order to bridge the physical digital divide. Examples include:

- *FlexM* [116] – a beam and joint construction kit that generates a digital representation of the structure.
- *CapStones* [117] – capacitive blocks that allow the physical manipulation of items on a touch screen.
- *StackBlock* [118] – a block based construction kit that captures the arrangement of the blocks to create a digital model.
- *3D Model Acquisition* [119] – computer vision based approach that tracks a model as it is built from blocks.

These approaches offer physical interaction with the design and intuitive creation and modification without software user interfaces slowing down the prototyping process. However, the authors have only reported the development of these tools and not how they impact the prototyping or design process.

One approach that could bring improvements to prototyping could be to combine different prototyping tools. Song *et al.* [120] presented a coarse–to–fine fabrication of 3D objects that combined 3D printed parts with a laser cut substructure. Using this approach the authors claim that there is a material cost savings and time savings of 25 % and 35 % respectively.

Gao *et al.* [121] developed this concept of multi–modal prototyping further by creating RevoMaker that combines a cuboid shape (containing functional components) and printing directly onto each of the faces to minimise support material and material wastage. With the added benefit of functional electronic components embedded in the object.

Mueller *et al.* [54] focus primarily on reducing fabrication time of prototypes through combining 3D printing and LEGO construction kits. Their approach was to locally adapt

[116] Eng, M. et al. (2006) *FlexM: Designing a physical construction kit for 3d modeling*
[117] Chan, L. et al. (2012) *CapStones and ZebraWidgets: sensing stacks of building blocks, dials and sliders on capacitive touch screens*
[118] Ando, M. et al. (2014) *StackBlock: Block-shaped Interface for Flexible Stacking*
[119] Miller, A et al. (2012) *Interactive 3D model acquisition and tracking of building block structures*
[120] Song, P. et al. (2016) *CofiFab: Coarse-to-Fine Fabrication of Large 3D Objects*
[121] Gao, W. et al. (2015) *RevoMaker: Enabling Multi-directional and Functionally-embedded 3D printing using a Rotational Cuboidal Platform*
[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*

the fidelity of the prototype: 3D printed parts where high fidelity was required and LEGO bricks where the fidelity was not a concern. This resulted in prototypes that could be fabricated 2.44 times faster on average.

2.5 Gap in Understanding

Prototyping is a critical activity in the development of new products, and is used throughout the design process. It is widely accepted that increased prototyping, of any form, leads to improved products and brings benefits to designers and design teams. Prototypes can have many different, and often overlapping, purposes: from exploring the design space, or testing a design concept, to communicating the designs to stakeholders, or demonstrating performance requirements have been met.

As prototypes are increasingly used more broadly in the development of new products, it is important to understand how the materials, techniques and tools used affect the outcome. The designer must choose a suitable representation for the question at hand and so a knowledge of the relative affordances and limitations of prototyping activities can lead designers to make a better choice to support their needs at a particular stage of the design process.

While the traditional design tools of sketching and CAD are ubiquitous, one limitation that became apparent was that the use of physical prototyping in the design process is hindered by its cost and time to fabricate designs. As a consequence, fewer design iterations are performed due to time and cost constraints; contravening best practice that shows more iterations bring benefits to the outcome of the design process. Furthermore, the fidelity and functionality of the required prototype need to be balanced against the time and cost to produce it [52] – i.e. a higher fidelity prototype is most expensive and time consuming to produce.

There has been significant research into improving prototyping holistically through strategic frameworks, however there has been little research into how to improve individual techniques. Some proposed methods to overcome the issues of prototyping around fabrication time and cost include; editable physical models [122], the use and reuse of existing products or components [12], speed up 3D printing through wire printing and laser cutting by sacrificing fidelity [108], [110]. Furthermore, methods for adapting LEGO to be more suited to higher fidelity prototyping have been presented [7].

From the literature, an apparent gap in the understanding and development of prototyping technologies and techniques has been identified. There is no single technique that

[52] Sass, L. and Oxman, R. (2006) *Materializing design: The implications of rapid prototyping in digital design*
[122] Lennings, A. et al. (2000) *Editable Physical Models for Conceptual Design*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[108] Mueller, S. et al. (2014) *WirePrint: 3D Printed Previews for Fast Prototyping*
[110] Beyer, D. et al. (2015) *Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates*
[7] Boa, D. et al. (2017) *Evolving lego: Prototyping requirements for a customizable construction kit*

affords appropriate levels of prototype fidelity, that can be rapidly fabricated and offer the low costs required in the early stages of the design process. The aim of the thesis is to address this shortcoming through the development of a disruptive approach to prototyping. In support of this aim, it would be beneficial to compare how different prototyping techniques are used in the design process. This would provide a description of their relative strengths and weaknesses, as well as user feedback from their use. This understanding would help steer the research and development of a solution to fill the gap in the prototyping field.

Chapter 3

Towards Hybrid Prototyping

3.1 Need for Comparison

Being able to choose a suitable prototyping technique at a particular stage in the product development process is critical to the success of the outcome [18]. Furthermore, Thomke [17] states that switching between prototyping methods at the right time can have benefits of reducing cost and overall development time. Consequentially, there needs to be an understanding of how prototyping techniques differ, and in particular, their relative affordances and limitations and how they impact the overall design process. It is self evident that such understanding would enable designers to make better and more informed decisions about which techniques to use, and when best to employ them. From this, the following preliminary research question was posed: "How do common prototyping techniques influence the behaviour, activities, and outcome in the design process?"

On the whole, prototyping techniques have been reported or studied individually, with only a handful of papers comparing multiple techniques. Table 3.1 summarises the different techniques compared by authors in literature.

Table 3.1 A table showing the different techniques compared in existing literature

Authors	Sketch	CAD Model	Const. Kit	Foam/ Card	3D Printed	Laser Cut	CNC Alu.
Hannah et al. [123]	●	●	●	●			●
Häggman et al. [124]	●	●		●			
Deininger et al. [87]	●	●		●	●		
Jensen et al. [70]				●	●	●	●

Hannah *et al.* [123] investigated how novice designers interpreted four different design representations: sketches, CAD models, low fidelity prototypes (LEGO or cardboard) and high fidelity prototypes (fully functional built from aluminium). They found that designers get more information and are more confident about a design when dealing with high fidelity prototypes over sketches.

Häggman *et al.* [124] investigated the use of sketching, CAD and foam modelling and how users responded to the different representations. They found the ideas were generated more quickly with foam model designs and that users found them more novel, aesthetically pleasing, and comfortable to use.

Deininger *et al.* [87] found that stakeholder feedback was affected by the embodiment of the prototype when comparing sketching, cardboard mock-ups, CAD models, and 3D

[18] Camburn, B. et al. (2015) *A Systematic Method for Design Prototyping*
[17] Thomke, S. H. (1998) *Managing Experimentation in the Design of New Products*
[123] Hannah, R. et al. (2012) *A user study of interpretability of engineering design representations*
[124] Häggman, A. et al. (2015) *Connections Between the Design Tool, Design Attributes, and User Preferences in Early Stage Design*
[87] Deininger, M. et al. (2017) *Does Prototype Format Influence Stakeholder Design Input?*
[70] Jensen, L. S. et al. (2018) *Prototyping in Mechatronic Product Development: How Prototype Fidelity Levels Affect User Design Input*

printed designs. However, they could not draw conclusions about which prototype was the most favourable for eliciting particular feedback.

Jensen *et al.* [70] studied the effect of fidelity on the users' perception of the design comparing cardboard, laser cut MDF, 3D printed, and CNC aluminium versions of the design. They found that fidelity does affect the perception of the prototype but that the techniques must be matched to the technical ability and knowledge of the audience. Furthermore, they observed that the design insights can be balanced against the resources and money spent (e.g. CNC Aluminium vs. cardboard) and that low fidelity prototypes can be of value and allow for a larger number of design iterations within the same budget constraints.

One of the shortcomings of these studies is that they only considering the outcome (e.g. ideas generated, level of stakeholder input) rather than the behaviour or activities the different techniques elicit and how these change during the design and prototyping process. While this goes some way to answering the preliminary research question, more work needs to be undertaken to be able to more fully understand the relative affordances and limitations of common prototyping techniques.

In order to address this gap in knowledge, a preliminary study was undertaken. The following section describes the study and discusses the findings.

3.2 Prototyping Techniques Study

This prototyping comparison study was first reported by the author at the Design Conference 2018 [4] and is expanded upon in this section. The study aimed to provide insights into how different prototyping techniques compare to each other and their relative affordances and limitations over the design process. It follows that the working hypothesis for the study is that there are differences in prototyping techniques with respect to the design activities, behaviours and outcomes they enable or inhibit. This aim necessitates the direct comparison of multiple techniques utilised in a common design task. The study is focussed on *proof–of–concept* prototypes (see Section 1.2.2) that are used in the early stages of the design process to explore design concepts.

3.2.1 Method

A group design task was organised to study how four different prototyping techniques were used in the production of concept designs for a common design brief. The four techniques investigated in the comparison study are summarised in Table 3.2. These were Sketching (see Section 2.3.1), Computer Aided Design (see Section 2.3.1), Cardboard Modelling (see Section 2.3.2), and Construction Kits (see Section 2.3.2). In this study the

[70] Jensen, L. S. et al. (2018) *Prototyping in Mechatronic Product Development: How Prototype Fidelity Levels Affect User Design Input*
[4] Mathias, D. et al. (2018) *Characterizing the Affordances and Limitations of Common Prototyping Techniques to Support the Early Stages of Product Development*

construction kit of choice was LEGO due to its familiarity and ubiquity. By selecting these methods, a spectrum of prototyping techniques is represented in the study: covering both physical and virtual, and high and low fidelity, as summarised in Table 3.2.

Table 3.2 A summary of the techniques used in the comparison study

Technique	Embodiment	Fidelity
Sketching	Virtual	Low-Medium
Computer Aided Design	Virtual	High
LEGO	Physical	Low
Cardboard Modelling	Physical	Low-Medium

The following sections describe the participants and materials used, and establish the experimental methodology of the study.

Participants

The study was performed with students studying undergraduate design degrees at two universities: University of Bristol, UK and University of Swinburne, Australia. The breakdown of participants is summarised in Table 3.3. The participants consisted of 24 Engineering Design students (University of Bristol) in the first year of their course, and 27 Industrial Design students (University of Swinburne) in the second year of their course.

Table 3.3 A summary of participants used in the comparison study

Institution	No.	Course	Mean Age
University of Bristol	24	1^{st} Year Engineering Design	19
University of Swinburne	27	2^{nd} Year Industrial Design	20

All the students had known and similar experience in sketching, CAD and cardboard modelling through their academic courses, but none could be considered experts in any of the prototyping techniques. Controlling for LEGO was not required as the skill level in using it is very low as it was originally designed as a toy accessible to children. All students reported that they had used LEGO previously. Parallel studies were undertaken in Bristol and Swinburne, in both cases the participants were randomly assigned into groups of four and each group was given one of the four prototyping techniques. While characteristics such as personality and creativity can affect the design process followed and output, as this study is investigating the impact of varying prototyping techniques alone, such characteristics are considered out of scope of this research. In this case, controlled solely through randomness in group member selection.

Prototyping Materials

The prototyping materials provided to the groups of participants were as follows:

- Sketching: A4 sketch pads, sketching pencils, coloured marker pens and fine-line pens.

- Cardboard: 1 and 2 ply corrugated cardboard, craft knives, hot glue guns, tape, wooden skewers and cocktail sticks.
- CAD: A computer per person, running Autodesk Inventor 3D Modelling Software.
- Construction Kits: A Classic Large Creative Brick Box consisting of 790 assorted LEGO pieces [125].

The groups could only use the prototyping technique they were assigned and were limited to the provided materials.

Design Task

The design brief was set as out as follows:

> "To design a novel, disruptive approach to personal transportation for 15–20 years' time."

The brief was deliberately chosen to permit a broad range of solutions that the participants could explore. Furthermore, the topic of transportation was familiar to all the participants and so it was not a prerequisite to have any engineering experience or to research the existing issues and limitations with the current approaches to understand the problem. Finally, it was asserted that the design brief did not favour a particular technique over another. For example, if the brief encouraged organic shapes then LEGO would be at a disadvantage due to its geometric constraints. Similarly, if the brief was for something tactile and hand held then CAD would be disadvantaged as it lacks physical interaction and a sense of scale in the designs.

Figure 3.1 shows a timeline of the study, highlighting the different phases of the design task as well as the administrative sections.

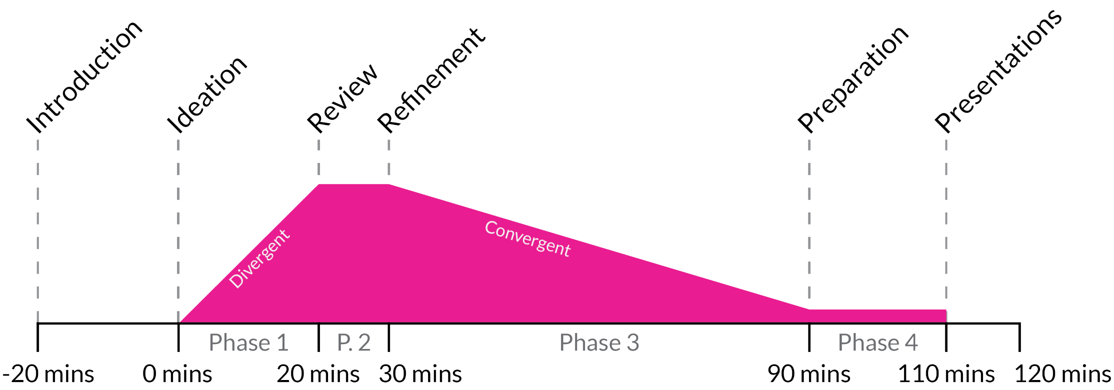


Figure 3.1 A timeline of the comparison study, showing the different phases of the design task.

After an introduction to the task, the groups had two hours to design and produce prototypes of their ideas and prepare a presentation to pitch their chosen idea. In the first 20 min, the groups were encouraged to come up with a broad range of ideas. These ideas would then be evaluated during the review phase with one concept being taken forward into the refinement phase for the rest of the session. The final 20 min of the allocated

[125] The LEGO Group. (2019) *LEGO Large Creative Brick Box*

time was for the groups to finalise their prototypes and write a short presentation. The timing started from the moment the groups were working on the design task.

Data Collection

The two forms of data collected in this study were:

- Time spent performing particular design activities over the course of the study.
- Reflections from the participants about their experiences using the prototyping techniques.

This data was collected in two ways. The primary method for the quantitative time data was through self-reporting forms that the participants had to fill in at 10 min intervals. The secondary method for the reflections was a questionnaire given to the participants after the task was completed. In both cases, each participant had to fill in the forms individually.

Self-Reporting Forms

The self-reporting method employed in this study was a derivative on the method used by Jonson [126] to study ideation tools. The self-reporting forms were completed every 10 min by the each participant for their group's activities over the course of the design task. An example of the self-reporting form for a single time interval can be seen in Table A.1. The form covered five design activities (Problem Structuring, Ideating/Generating new ideas, Refining/Developing ideas, Evaluating/Critiquing Ideas, and Collaborative Work) with a catch-all for any other activity performed in the 10 min intervals. It allowed the groups to record their engagement in the activities to three levels: None, Some, and A lot. This coding scheme of design activities and levels binning was agreed by the group of researchers overseeing the study in the UK and Australia.

During the introduction to the session, the participants were briefed on how to fill in the self-reporting forms with descriptions and examples of the different design activities listed on the form. It was also explained that the activities were not mutually exclusive, allowing the participants to select 'A lot' for more than one activity if that reflected how they had spent their time. While this approach has its limitations around the accuracy of participants' self-reporting, it was chosen as a compromise between capturing useful data and not excessively influencing the design task.

Reflective Questionnaire

This questionnaire comprised of six questions: the first three were structured Likert scale questions, the second three allowed for open ended responses. The questions were as follows (with the areas to consider in brackets):

1. How easy was it to use the prototyping technique to communicate the ideas in the following phases? (Ideation, Review, and Refinement).
2. How easy was it to use the prototyping technique to evaluate the following aspects of a design? (Moving Parts/Interaction, Function/Features, Scale/Relative

[126] Jonson, B. (2005) *Design ideation: The conceptual sketch in the digital age*

Arrangement, Aesthetic/Form Detail, Mode of Operation/Process).

3. How easy was it to use the prototyping technique to perform the following design tasks? (Generating Ideas, Refining Ideas, Selecting the Best Idea, Developing the Chosen Idea).

These questions were all answered on a Very Difficult to Very Easy scale for each of the options. The rationale behind these questions was to capture how suitable the different prototyping techniques were for use in various phases in the design process and in representation design aspects.

The questions for the open-ended responses were as follows:

4. To what extent do you feel the prototyping technique used influenced your design?
5. How easy was it to explore changes to your design via the prototype?
6. How much did you have to explain the idea to your group members in addition to showing them your prototype?

The rationale behind the last three questions was to capture the participants' views and opinions on how they felt about using the different prototyping techniques. The information provided by the questionnaire supplemented the self-reporting forms in capturing data on the design activities that the prototyping techniques elicit. Furthermore, care was taken to ensure that all the questions were fair to the different prototyping techniques.

3.2.2 Results

The results are split into self-reporting and reflective questionnaire sections. Some examples of the prototyped concepts that the groups created are shown in Figure 3.2.

Self-Reporting Forms

Each participant self-reported during the design task, this resulted in four sets of data per group. In order to reach a group consensus for each time interval, the responses were weighted (8 min for 'A Lot', 2 min for 'Some' and 0 min for 'None') and the median calculated. This was repeated for the six design activities. The results for the four techniques are shown in Figure 3.3.

In order to draw relative comparisons between the different techniques the absolute time values were split into the four phases of the task (see Figure 3.1): ideation (0–20 min), review (20–30 min), refinement (30–90 min) and presentation preparation (90–110 min). To focus on the design task, the introduction and presentation time periods were not included. The values were averaged across the phase and then binned into the 'None' (○), 'Some' (◑), and 'A lot' (●) categories used in the self-reporting forms. The results are shown in Table 3.4.

Reflective Questionnaire

To get a group consensus in the Likert scale questions, the median of the groups' responses was taken. The results for the first three questions can be seen in Figures 3.4a

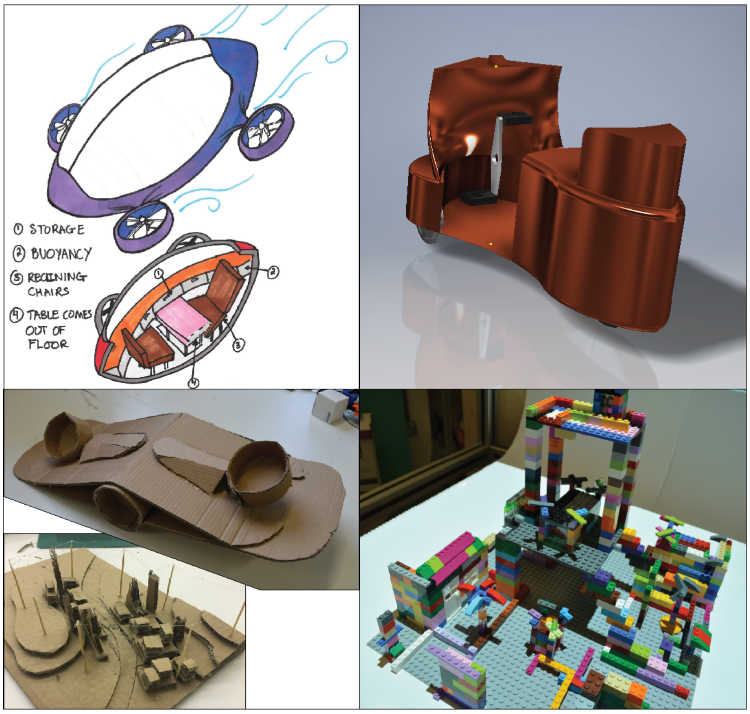


Figure 3.2 Examples of the prototypes produced during the comparison study. Clockwise from top left: Sketching, CAD, LEGO, Cardboard.

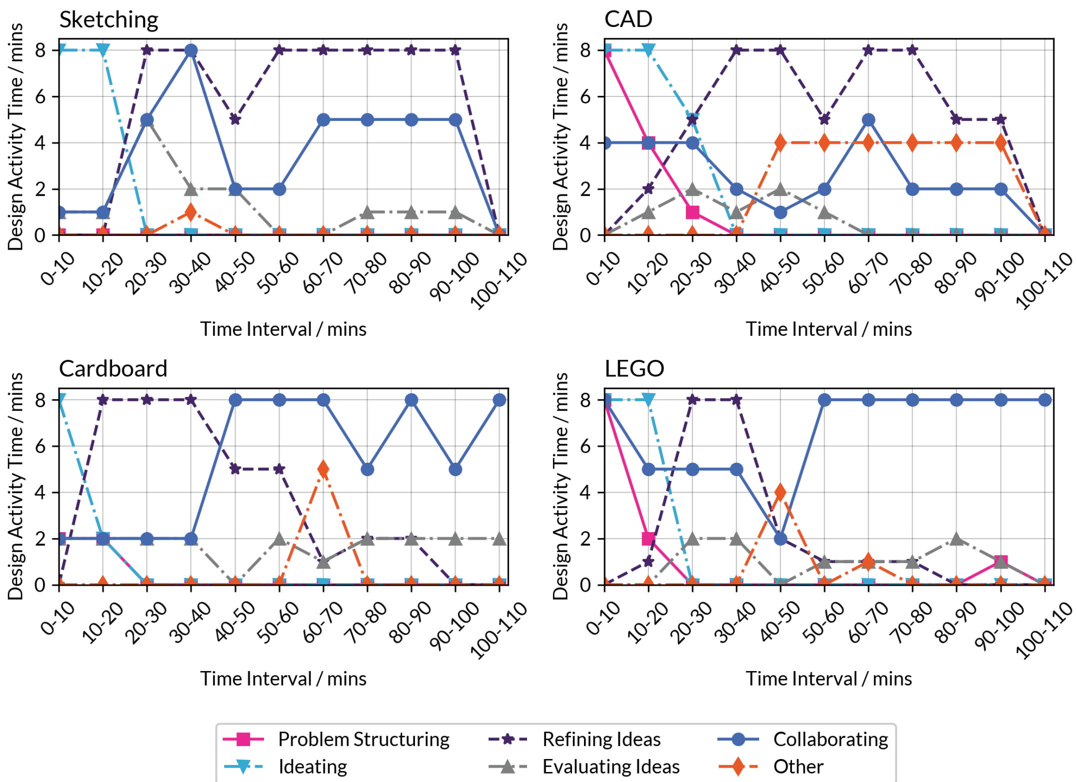


Figure 3.3 Plots of the time spend in each design activity over the time intervals for the four prototyping techniques

Table 3.4 Time spent performing design activities in the three main phases of the design task for (a) Sketching, (b) CAD, (c) Cardboard, and (d) LEGO. The time was binned into the 'None' (○), 'Some' (◑), and 'A lot' (●) categories

(a) Sketching

	Ideation	Review	Refine.
Structuring	○	○	○
Ideating	●	○	○
Refining	○	●	●
Evaluating	◑	●	◑
Collaborating	◑	●	◑
Other	○	○	◑

(b) CAD

	Ideation	Review	Refine.
Structuring	●	◑	○
Ideating	●	●	○
Refining	◑	●	●
Evaluating	◑	◑	●
Collaborating	◑	◑	◑
Other	○	○	◑

(c) Cardboard

	Ideation	Review	Refine.
Structuring	◑	○	○
Ideating	●	○	○
Refining	◑	●	◑
Evaluating	◑	◑	◑
Collaborating	◑	◑	●
Other	○	○	◑

(d) LEGO

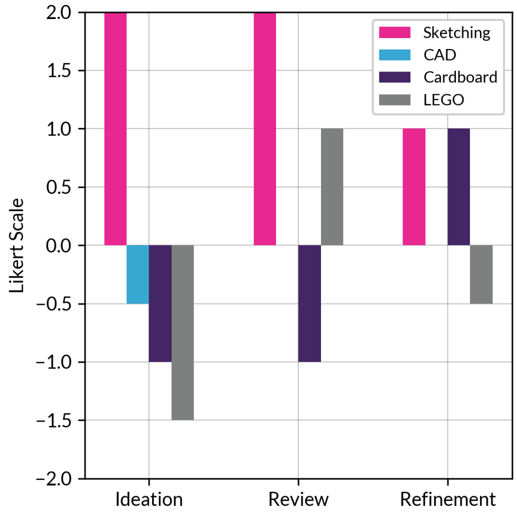
	Ideation	Review	Refine.
Structuring	●	○	○
Ideating	●	○	○
Refining	◑	●	◑
Evaluating	○	◑	◑
Collaborating	●	●	●
Other	○	○	◑

to 3.4b, respectively.

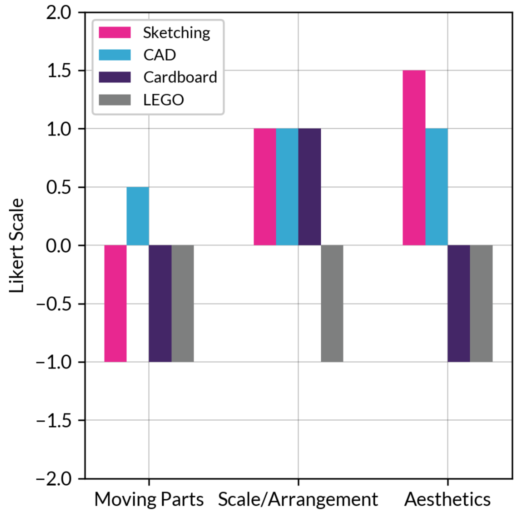
The open-ended responses to questions 4-6 were analysed using a coding scheme. In question 4 the answers were coded based on whether the technique inhibited or enabled their designs This was performed using the presence of keywords such as 'limited' or 'facilitated'. Question 5 was coded for sentiment of 'easy' or 'difficult'. The LEGO and Cardboard groups showed some disagreement amongst themselves. Responses to question 6 were coded using a scale based on the level of explanation required: 'none', 'some explanation', and 'substantial explanation'. The coded responses are summarised in Table 3.5.

Table 3.5 Coded responses to the open-ended questions of the reflective questionnaire

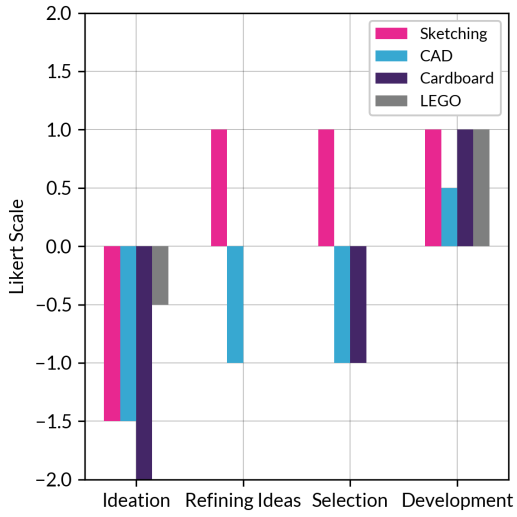
	Sketching	CAD	Cardboard	LEGO
Q4: Influenced your design?	Facilitated	Limited	Limited	Limited
Q5: Ease of changes?	Easy	Difficult	Easy	Easy
Q6: Explanation required?	Some	Substantial	Some	Substantial



(a) Q1: How easy was it to use the prototyping technique to communicate the ideas in the following phases?



(b) Q2: How easy was it to use the prototyping technique to evaluate the following aspects of a design?



(c) Q3: How easy was it to use the prototyping technique to perform the following design tasks?

Figure 3.4 The results of questions 1-3 of the reflective questionnaire. Answer scale: 2 (Very easy), 0 (Neutral), -2 (Very difficult).

3.2.3 Discussion

From the self-reporting forms (see Table 3.4), several observations can be made. This section highlights these observations and discusses the potential underlying reasons.

It was interesting to note that sketching group spent no time structuring the problem and dived straight into generating ideas. While the LEGO and CAD groups discussed the task within their groups and only started using their prototyping technique once they were happy to proceed. It is contended that this behaviour arises largely because the groups were strictly limited to their prototyping technique – so only the sketching group could augment their early ideation discussions with quick, light-weight, low effort sketches, while LEGO and CAD required a more methodical, hierarchical approach to representing their designs. This was also shown in the responses to questions 1 and 3 in the reflective questionnaire (see Figure 3.4), where sketching was considered to be easy to use in Ideation, but cardboard, LEGO, and CAD were considered to be difficult to very difficult.

Despite the differences in structuring the problem, all the groups reported high levels of ideation activity at the start that dropped off as the task progressed. This was expected as the groups were encouraged to think divergently during the Ideation phase but then to choose and refine an idea in the Review and Refinement phases. A caveat to the reported results is the fact that self-reporting does not capture how the group were using their prototyping technique but rather whether they had been performing a design activity.

The sketching and CAD groups spent more time refining their chosen ideas than the cardboard and LEGO groups. As the cardboard and LEGO groups were aware of the limitations in fidelity of their prototyping techniques (A LEGO group said, "we wanted to create something that could be effectively presented with LEGO") they did not strive for high levels of aesthetic detail but rather prototypes that were sufficient to explain their concepts. Conversely the sketching and CAD groups were using higher fidelity techniques (The sketching group commented that sketching "gave [them] a lot of freedom in complexity of design and detail"). They reported spending more time producing prototypes with higher levels of detail – potentially for aesthetic gain rather than meaningful design improvements. This was supported by the responses to the reflective question (see Table 3.5, Question 4), "did the prototyping technique influence the design?". The cardboard and LEGO groups stated that their "technique limited their designs", while the sketching group stated "it facilitated them". Despite the higher fidelity, the CAD group stated that using CAD software was potentially limiting on their design freedom as "complex shapes were difficult to create".

The concept of sunk cost in design tools was explored by Viswanathan and Linsey [127] and is relevant in explaining the attitudes of the groups to the time and perceived effort of making changes. When asked how easy it was to explore changes with their prototyping technique (reflective question 5) most groups referred to the time to create their designs or their lack of ability in the technique. The sketching group said changes were easy as they could quickly "draw over" designs, while the CAD group said changes were difficult and time consuming, and that it "was often easier to totally rebuild than to adjust" designs. On the whole the cardboard and LEGO groups thought that making changes were easy, however there was some disagreement within the groups. This disagreement stems from the apparent size of changes with small adaptations being achievable but large changes considered too difficult or time consuming to perform. While the groups using LEGO viewed its orthogonality as a limitation, the reconfigurable nature

[127] Viswanathan, V and Linsey, J. (2011) *Understanding physical models in design cognition: A triangulation of qualitative and laboratory studies*

of brick interfaces helped lower the effort required in making changes and encourages reconstruction and reuse of parts – an affordance not present in the other prototyping techniques.

There was little difference in the levels of evaluating reported by the groups with all the groups reporting some evaluating throughout the design task. However, there was one notable exception, the LEGO groups reported that they did no evaluating during the ideation phase. As the design task was group based, it was unsurprising to see that each prototyping technique had at least some collaborative activity over the entire session. However, the groups using physical techniques (LEGO and cardboard) reported more collaboration amongst themselves, particularly in the refinement phase. This emphasis on collaboration comes from the fact that the LEGO and cardboard groups had a physical object that they could interact with and discuss effectively becoming an intermediary object [28]. In their reflections, the groups using LEGO and Cardboard stated that on the whole communicating ideas with their technique was difficult and that they required supplementary discussion and in some cases substantial explanation. Consequently, the lack of fidelity and increased ambiguity in the physical techniques forced more dialogue between designers to communicate designs.

Reflections on Study

In the context of the wider thesis, there are two reflections on the study that need to be addressed. The first reflection is the choice of design task. This thesis focusses on user-driven products, and so the design task used did not fit within this scope. Changing the design task would provide more useful information about how participants use the different prototyping techniques. However, choosing a product to design that would not provide any design fixation would be challenging and require careful consideration.

The second reflection is the data capture. Capturing design activities through self-reporting has issues around accuracy and interference with the design task. Instead, it would be better to collect the output from the prototyping efforts: the number of iterations, size and scale of modifications, and time to produce different iterations. These measurements would be quantitative and more straightforward to capture. The data would provide a more useful comparison between the prototyping techniques, and give greater insight into how the technique affects the speed and frequency of prototyping.

3.2.4 Findings

In the discussion, there are two threads that stand out from the results and the participants' comments:

1. Design fixation and sunk cost effect were prominent as the participants were reluctant to consider alternative designs from the one they had already produced. These effects were exacerbated by the effort and time to make changes or modifications to the designs.

[28] Boujut, J.-F. and Blanco, E. (2003) *Intermediary Objects as a mean to foster Co-operation*

2. Lower fidelity prototypes, while giving rise to more discussion, were ambiguous and had to have extensive explanation to communicate the designs. However, high fidelity techniques resulted in the participants trying to create a prototype that 'looked good' rather than one that answered design questions.

From these two findings, it is apparent that there are issues that need resolving around the speed and effort of prototyping while producing prototypes of appropriate fidelity. A slower fabrication time means that the combination of time to create the initial prototype and to enact changes prevents designers exploring alternative ideas or developing iterations.

The time, cost and effort of prototyping, described in the first finding, could be addressed in two ways: either to reduce the difficulty of modifications, or to fabricate the prototype faster. In both cases, the driving factor is to reduce time between design iterations to help designers enact they thoughts more quickly and to help reduce design fixation. Camburn *et al.* [12] posit ways in which these issues can be addressed, for example by prototyping in parallel, isolating subsystems, or relaxing design requirements.

From the second finding, fidelity is a key part of prototyping. Sauer and Sonderegger [69] and Jensen *et al.* [70] found that prototype quality and fidelity played an important role in how stakeholders perceived the design. This is not limited to physical prototypes, for example, Macomber and Yang [82] investigated how sketch quality influenced stakeholder feedback and found that realistic and clean sketches were ranked higher than rough sketches. Furthermore, Camburn *et al.* [12] state that higher fidelity representations lead to accurate interpretation of the design. Consequently, in the design of *user-driven* products, high fidelity prototypes are required to elicit useful stakeholder and user feedback on the design. However, low fidelity prototypes are still valuable as they provide a high level design insight to cost/time ratio. It is apparent that the fidelity of a prototype needs to be appropriate for the situation and within the time and cost constraints of the current stage in the design process.

There is tension between the need for faster and cheaper prototyping and the utility of higher fidelity representations. Addressing these opposing issues is currently unachievable with current prototyping techniques, with no technique allowing designers to quickly modify or create their designs while still providing high–fidelity representations. Several potential approaches to addressing this include:

- The development of new technologies that permit the faster/cheaper fabrication of

[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*

[69] Sauer, J. and Sonderegger, A. (2009) *The influence of prototype fidelity and aesthetics of design in usability tests: Effects on user behaviour, subjective evaluation and emotion*

[70] Jensen, L. S. et al. (2018) *Prototyping in Mechatronic Product Development: How Prototype Fidelity Levels Affect User Design Input*

[82] Macomber, B. and Yang, M. C. (2011) *The Role of Sketch Finish and Style in User Responses To Early Stage Design Concepts*

[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*

prototypes.
- The refinement and improvement of current prototyping techniques in fabrication time and material costs.
- A combination of existing techniques that could be implemented to reduce fabrication times and material costs.
- Training for individual designers to develop skills for creating/modifying prototypes more quickly.

The first option would require significant research efforts into the technical aspects of manufacturing to realise a novel technology that could cause a paradigm shift in how prototyping is performed (e.g. the rise of additive manufacturing and rapid prototyping). The second option could bring marginal gains to prototyping however it is unlikely to result in the step changes required to impact the barriers to prototyping in the design process. The last option of investigating how to improve a designer's skill and ability is not feasible without longitudinal studies and so are out of scope for this research.

Therefore, it is contended that a combination of techniques would be more suitable for prototyping in the early stages of the design process as complementary affordances could be matched and limitations overcome. However, there needs to be consideration around the suitability of combining different techniques. This can include the compatibility of materials, and the methods of interfacing the different techniques together, as well as more practical considerations such as tool and machinery requirements or health and safety precautions.

3.3 Introducing Hybrid Prototyping

Hybrid Prototyping (HP) is the term given to an approach to prototyping that couples two different prototyping techniques. This coupling aims to combine the benefits and affordances of both techniques, while overcoming their respective limitations. In the context of prototyping in the early stages of the design process, the goal of Hybrid Prototyping is to bring the benefits of reduced fabrication time and cost, while maximising the prototype's utility.

The following sections cover existing and potential combinations of techniques that could be used as Hybrid Prototyping tools, before justifying the coupling of LEGO and 3D printing as the basis of the research investigated in this thesis.

3.3.1 Combining Techniques

The combining of techniques will be focussed on physical prototyping techniques, described in Section 2.3.2. Hybrid prototypes of two virtual techniques (see Digital Sketch

Modelling [88]) or of a physical and a virtual techniques (see Mixed Prototyping [128]) exist. These Hybrid Prototypes are considered out of scope for this research as it has been shown that physical prototyping faces greater barriers to its use in the design process. Namely, that prototype tangibility and physicality provide benefits to the *learning* and *communication* purposes of prototyping [22], [91].

There are several requirements for choosing two techniques to combine as a Hybrid Prototype. These include:

- The techniques are suitably different to leverage their respective strengths. For example, the prototyping techniques could differ on the following:
  - Cost: equipment/tool requirements, material costs, reusability of parts.
  - Fabrication time: slow vs. quick to produce prototypes.
  - Fidelity: primitive forms vs. finely detailed prototypes.
  - Skill/Accessibility: technical ability required to use the tool.
- Both techniques can interface (or be joined) with each other without significant effort on the designer's behalf – e.g. sculpting clay over a wooden frame. However if digital fabrication techniques are used (i.e. CNC/3D printing), this interfacing could be managed by automated tools that create the parts.

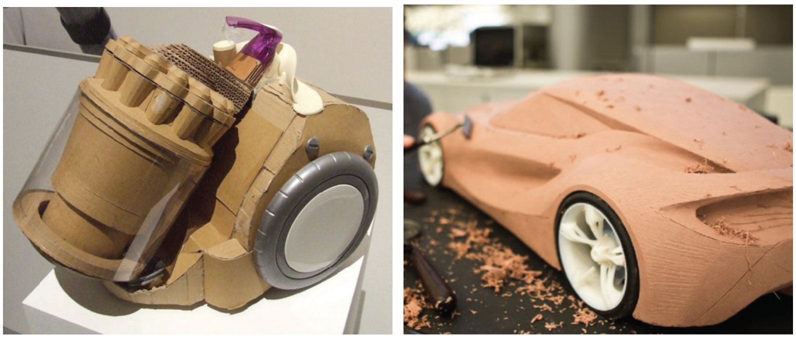
Existing Examples

While the term Hybrid Prototyping is new, there are reported examples, in both industry and literature, of combinations of prototyping techniques that could be considered to be hybrid prototypes.

In industry, Dyson [13] uses a mix of cardboard and plastic parts in the development of new vacuum cleaners (see Figure 3.5a). The plastic parts are elements of the design that are fixed from previous iterations, while the cardboard parts are still being designed allowing cheap fabrication, modification and editability. Another example includes using sculpting clay over a fixed frame to generate the body shape of cars in the automotive industry [129] (see Figure 3.5b). The underlying structural frame gives the rough shape and support for the prototype while the clay allows the designers to create detailed, complex curves, that can be easily modified.

In literature, laser cut sheet plastic and low cost 3D printing have been combined to accelerate low fidelity fabrication [110], allow the fabrication of large scale 3D objects [120],

[88] Ranscombe, C. and Bissett-Johnson, K. (2017) *Digital Sketch Modelling: Integrating digital sketching as a transition between sketching and CAD in Industrial Design Education*
[128] Barbieri, L. et al. (2013) *Mixed prototyping with configurable physical archetype for usability evaluation of product interfaces*
[22] Youmans, R. J. (2011) *The effects of physical prototyping and group work on the reduction of design fixation*
[91] Kelley, T. and Littman, J. (2001) *The Art of Innovation*
[13] James Dyson Foundation. (2010) *Engineering Box - Teacher's Pack*
[129] Singh, K. (2006) *Industrial motivation for interactive shape modeling: a case study in conceptual automotive design*
[110] Beyer, D. et al. (2015) *Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates*
[120] Song, P. et al. (2016) *CofiFab: Coarse-to-Fine Fabrication of Large 3D Objects*



(a) A cardboard and plastic prototype of a vacuum cleaner [13]

(b) A clay and frame prototype of a scale car

Figure 3.5 Examples of existing Hybrid Prototypes in industry

and to house functional components within printed parts [121]. Similarly, construction kits (in the form of LEGO) have been combined with low cost 3D printing [54] to reduce fabrication times by sacrificing fidelity.

Potential Combinations

From the general requirements for combining techniques in HP, there are several potential combinations that could yield benefits in prototyping time and cost. The following list posits some of these potential combinations:

- *Foam Modelling & Laser Cut Sheet Plastic* – The sheet plastic can be used to create the approximate shape of the prototype with detailed foam parts attached to it providing the higher fidelity/organic shape/fine detail.
- *Truss Construction Kit & CNC Machined Parts* – A truss based construction kit, such as Meccano, allows large, sparse structures to be easily constructed, with CNC machined parts from a soft, easily worked material such as plastic or wood adding the necessary detail and form.
- *Block Construction Kit & Plasticine* – Similar to the two previous examples, the main form of the prototype can be created out of a block construction kit (i.e. LEGO), with the organic form and detail added through the use of plasticine to mould the shapes unachievable with LEGO.

However, although there are many combinations that could be investigated to establish the feasibility of and characterise Hybrid Prototyping, only one was selected.

3.3.2 Chosen Combination

LEGO and low cost 3D printing were chosen as the combination to investigate in this thesis for several reasons. As shown by Mathias *et al.* [4], the common prototyping tech-

[121] Gao, W. et al. (2015) *RevoMaker: Enabling Multi-directional and Functionally-embedded 3D printing using a Rotational Cuboidal Platform*
[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*
[4] Mathias, D. et al. (2018) *Characterizing the Affordances and Limitations of Common Prototyping Techniques to Support the Early Stages of Product Development*

niques occupy a spectrum of fabrication time, cost and fidelity. This is illustrated in Figure 3.6. LEGO and 3D printing sit at opposite ends of this spectrum and so have opposing strengths (and weaknesses). Therefore coupling them together in a HP meets the first requirement stated at the start of Section 3.3.1.

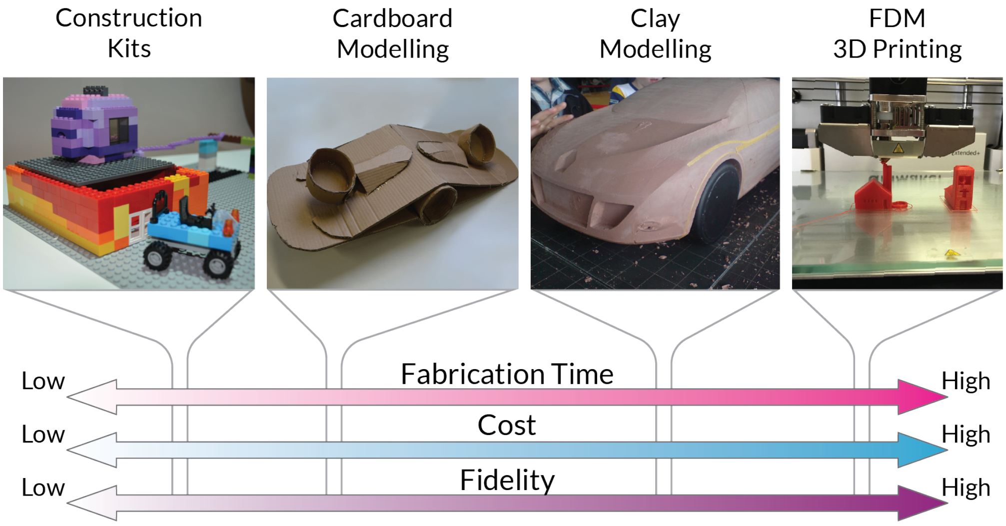


Figure 3.6 An illustration showing a spectrum of common prototyping techniques

Secondly, the combination has been demonstrated before [54], highlighting the potential benefits around fabrication time. However, the demonstration described the tool and how it worked rather than evaluating it as a prototyping technique. Finally, these methods possess some common properties which makes their coupling more straightforward. Meeting the second requirement of HP. These properties are:

- Similarity of construction materials – i.e. low cost thermoplastics.
- The required level of tolerance between techniques is achievable – i.e. the method of interfacing 3D printed parts and LEGO does not require significant research effort.
- No requirement for health and safety precautions – i.e. management of dust/swarf from CNC machining and foam modelling, or fumes from laser cutters.
- No requirement for tools or expensive machines, and therefore a lower skill requirement.

3D printers offer affordable, bespoke parts with nearly unlimited complexity and form, and consequently have become a common part of the prototyping process [98]. The choice of exploring the prototyping potential of 3D printing is supported by Camburn *et al.* [12] who state that

[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*
[98] Campbell, I. et al. (2012) *Additive manufacturing: rapid prototyping comes of age*
[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*

> “there are opportunities for seminal work in integrating design science with the open-source movement, and to explore the full capabilities of additive manufacturing as a prototyping tool.”

On the other hand, LEGO allows engaging and playful construction of low fidelity, physical models. Furthermore, once bought, LEGO is reusable and reconfigurable therefore minimising the waste of materials and reducing costs of successive design iterations.

Coupling low cost 3D printing and LEGO introduces a level of fidelity unachievable by LEGO alone while maintaining the flexibility and reconfigurability of a construction kit. This builds on some of the improvements that Boa *et al.* [7] suggested could be made to LEGO to increase its usefulness as a design tool.

Chapter 4 outlines the aims and research methodology of the thesis, and describes the technological approach to combining LEGO and 3D printing.

[7] Boa, D. et al. (2017) *Evolving lego: Prototyping requirements for a customizable construction kit*

Chapter 4

Research Framework

4.1 Aim

In Chapter 1, the general aim for the thesis was stated as "improving the use of prototyping in the early stages of the design process". This overall aim was refined through the literature review in Chapter 2 and the exploratory study in Chapter 3. From the literature review, the definition of prototyping was explored and the significance of prototyping in the design process was elucidated. It was also shown that there are many different prototyping techniques that are used in the early stages of the design process. Due to the importance of prototyping and the breadth of possible approaches, there have been significant research efforts to improve the prototyping process and the techniques employed – to improve the cost, quality and time in the product development process. These improvements can be achieved via three mechanisms:

- *Activity Improvements* – improving overall prototyping activities in the design process to increase efficiency of the process and reduce unnecessary prototyping efforts.
- *Tool Improvements* – improving existing prototype fabrication techniques to reduce fabrication time and increase stakeholder participation.
- *Disruptive Approaches* – developing novel prototyping methods that disrupt the existing approaches.

This thesis focuses on a *Disruptive Approach* to improving physical prototyping in the design process. Physical prototyping provides tangibility to ideas and an intuitive understanding of the design [66]. As well as better opportunities for learning about the design space [24], communicating design ideas [28], and engaging stakeholders [91]. However, the most significant barriers to the use of physical prototypes were found to be around the time it took to fabricate the designs, and the material cost associated with creating a physical artefact [18], [19].

The preliminary study (e.g. Chapter 3) echoed these reports in literature, with participants stating that speed of creating prototypes (and subsequently modifying them) limited their ability to create and iterate representations of the designs. It was also found that the level of fidelity of the prototypes affected how the participants perceived their ideas. Chapter 3 concluded by positing hybrid prototyping as a potential solution to creating prototyping tools that afford high fidelity prototypes but also can be rapidly and cheaply fabricated.

The key findings can be summarised as:

[66] Donati, C. and Vignoli, M. (2015) *How tangible is your prototype? Designing the user and expert interaction*
[24] Yang, M. C. (2005) *A study of prototypes, design activity, and design outcome*
[28] Boujut, J.-F. and Blanco, E. (2003) *Intermediary Objects as a mean to foster Co-operation*
[91] Kelley, T. and Littman, J. (2001) *The Art of Innovation*
[18] Camburn, B. et al. (2015) *A Systematic Method for Design Prototyping*
[19] Otto, K. and Wood, K. (2001) *Product Design: Techniques in Reverse Engineering and New Product Development*

- Fabrication time and material costs of physical prototypes are the greatest barriers to their use.
- Fidelity is important for stakeholder perception and feedback and heavily influences fabrication time.
- Hybrid prototyping is a potential solution to these problems.

To this end, the specific aim of this thesis is:

> "To investigate and characterise the coupling of LEGO and 3D printing to reduce prototype fabrication time and material use, while preserving appropriate fidelity."

This chapter begins by outlining the research questions used to achieve the thesis' aim. The research questions are then contextualised against the research methodology framework that was used to move from the literature review and preliminary study to the formulation and answering of the research questions. Once the methodology is explained, this chapter develops and summarises the components of the technology platform used throughout the thesis. The chapter finishes by identifying objectives to answer the research questions, and outlines the structure of the thesis.

4.2 Research Questions

Based on the generation of the Aim (explored in Section 4.1), along with findings from the literature review and exploratory study, a number of challenges were identified. These were formalised into three research questions:

1. What are the potential time and material savings from Hybrid Prototyping?
2. How can Hybrid Prototyping be implemented in practice?
3. How can the potential time and material savings be maximised?

These are described in more detail in the following sections.

In support of these research questions, four objectives have been developed to provide direction and guide the answering of the research questions. These are outlined, along with their outcomes, in Section 4.6.1.

4.2.1 Research Question 1

It has been shown through the research clarification that the barriers to physical prototyping are typically around the cost, both in time and materials, of creating a prototype. In Chapter 3, Hybrid Prototyping was posited as a potential approach to reducing fabrication time and material usage. However, as it is a novel prototyping technique, the possible time and material savings have yet to be investigated or characterised. This leads to this first research question:

> "RQ1: What are the potential time and material savings from Hybrid Prototyping?"

As this question focuses on a gap in the current knowledge of prototyping, addressing it requires original research taking the form of a descriptive study. The method for creating LEGO and 3D printed HPs is described in Section 4.4. Based on this method, the preliminary strategies for generating HPs and the study investigating their benefits are described in Chapter 5.

4.2.2 Research Question 2

As this research considers physical prototyping in the design process, it is critical that the findings are feasible and can be realised in the real world as a useful prototyping tool. This leads to the second research question:

> "RQ2: How can Hybrid Prototyping be implemented in practice?"

This question considers how the findings from RQ1 can be implemented as a practical tool. In order to address it, a combination of literature review and original research needed to be employed. The key design and fabrication rules for existing implementations of prototyping tools need to be identified from literature and best practice. From this, a set of rules for implementing Hybrid Prototyping can be created and evaluated in a descriptive study. The core focus of the study being whether Hybrid Prototyping can be practically employed in the creation of physical prototypes. The key metrics considered in the study are described in Section 4.4.2.

The strategies and considerations for implementation of HPs and their impact on the metrics are reported in Chapter 6.

4.2.3 Research Question 3

The third research question builds on the first and second questions. With the potential benefits shown, and achievable implementation developed, is it possible to improve these benefits? Consequentially, the third research question is:

> "RQ3: How can the potential time and material savings be maximised?"

This considers how the fabrication time and material usage can be reduced even further. This will evaluate different strategies that could be used to further improve the time and material savings when using Hybrid Prototyping techniques. The development of the resulting approaches will be supported by literature and evaluated in case studies to illustrate their benefits. The validity of the findings will be discussed in the presentation of the results. Chapter 7 explores and investigates different strategies that could be employed to maximise the benefits of HPs.

4.3 Research Methodology

The overall research methodology of this thesis aligns with the defacto methodology used in the design field – the Design Research Methodology (DRM) framework [130]. Figure 4.1 shows the four stages of the framework. The general stages are as follows:

1. *Research Clarification* – the overall aim and research goal is determined, typically through literature review.
2. *Descriptive Study I (DS-I)* – develop understanding of the context within which the research aim sits and to clearly identify the areas that will need addressing, typically through literature review and/or data analysis.
3. *Prescriptive Study (PS)* – develop and evaluate the methods and support for addressing the key areas identified in DS-1.
4. *Descriptive Study II (DS-II)* – identify and evaluate the effects of the new method on the intended task.

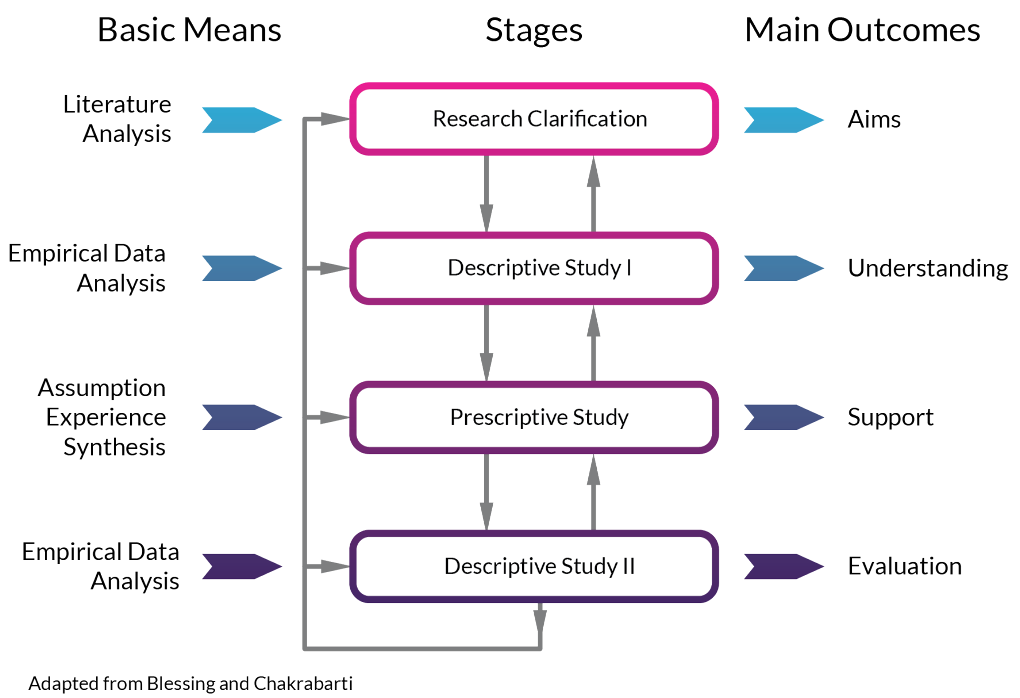


Figure 4.1 The Design Research Methodology framework [130]

Figure 4.2 shows how the DRM is applied to this thesis. This consists of the Research Clarification stage, followed by a comprehensive Descriptive Study I and a comprehensive Prescriptive Study. The thesis finishes with an initial Descriptive Study II.

The aim of the thesis was determined during Research Clarification through an initial literature review and an exploratory participant based study. The outputs from Descriptive Study I were the research questions. These were developed through the combination of a more extensive literature review (Chapter 2) and the exploratory study (described in Chapter 3). Throughout this process, there was a continuous iteration between Descrip-

[130] Blessing, L. and Chakrabarti, A. (2009) *DRM, a Design Research Methodology*

tive Study I and Research Clarification as the thesis aim and research questions evolved in accord with findings from literature review, scoping study and technology exploration. The research questions, discussed in Section 4.2, relate to the benefit, development, and implementation of Hybrid Prototyping. These questions are addressed in the Prescriptive Study stage, through the development and testing of the Hybrid Prototyping tool. The tool is then evaluated against case studies with the results and discussion forming an initial Descriptive Study II.

To achieve the aim and to answer the research questions, several research objectives have been outlined. These objectives, and how they fit into the structure of the thesis, are covered in more detail in Section 4.6.

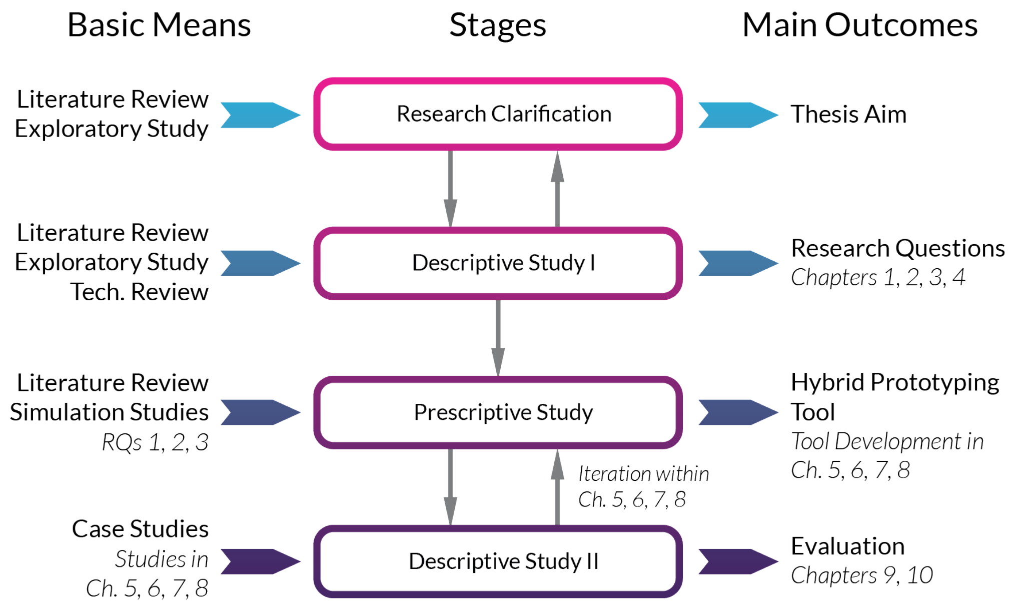


Figure 4.2 The Design Research Methodology framework as applied in this thesis

4.3.1 Scope

As first discussed in Chapter 1, 75 % of product costs are committed in the early stages of the design process [25]. This means that decisions made in these stages can have a significant impact on the overall development costs. Hence, research that accelerates the early stages of the design process not only directly saves time and cost, but by virtue of these savings can enable greater design iteration and refinement – improving the design outcome. Both of which can positively impact the overall development costs. It follows that *proof–of–concept* (see Section 1.2.2) prototypes should be the focus of this thesis.

Furthermore, in the design of *user–driven* (e.g. household appliances and consumer electronics) products (see Figure 1.3), the tools used to prototype the appearance, shape, and form have significant similarities – even between different classes of products. This means that research into form based prototypes (as opposed to function based ones) is more generalisable and extensible from case studies or example implementations.

[25] Ullman, D. G. (2003) *The Mechanical Design Process*

Therefore, the scope of this thesis will be focussing on form based *proof–of–concept* prototypes of *user–driven* products in the early stages of the design process.

4.4 Experimental Method

As previously stated in Section 3.3.2, LEGO and 3D printing were chosen as the candidate techniques to couple because they have opposing strengths (and weaknesses) and have complementary properties that allow their coupling. This approach of combining techniques of mixed speed, cost, and fidelity to leverage benefits has been taken by the following examples in literature:

- Song *et al.* [120] used laser cut sheets and 3D printing to decompose and then assemble large scale 3D objects.
- Mueller *et al.* [54] combined LEGO and 3D printing to create mixed fidelity prototypes.
- Beyer *et al.* [110] attached high fidelity 3D printed parts on to assembled laser cut sheets.
- Mueller *et al.* [108] developed hybrid printing where crude wire-frame printing was combined with normal high fidelity printing.

In this thesis, the approach taken uses LEGO to occupy the internal volume of a prototype, with 3D printing providing high-fidelity surfaces to attach onto the LEGO. There are close parallels with CNC machining where the LEGO is a 'rough cut' – forming the quick, approximate shape, and the 3D printing is a 'finishing pass' – creating high fidelity detail more slowly.

Furthermore, the papers identified at the start of this section, all developed software tools that could be used in support of creating prototypes. These demonstrate the validity of a creating software tool. Therefore, it follows that creating a HP software tool, not only allows the coupling of LEGO and 3D printing to be investigated, but creates the opportunity for this tool to be evaluated as a prototyping tool in further studies. This aligns with the *support* output from the Prescriptive Study stage described in Section 4.3.

4.4.1 Method

Due to the broad nature of prototyping and the variety of designs that could be investigated, there is a need to be able to quickly explore the design space. Similarly, there are a large number of factors to test and measure in the creation of a Hybrid Prototyping tool. It follows, that a computer–based simulation approach should be used to investigate coupling of 3D printing and LEGO.

[120] Song, P. et al. (2016) *CofiFab: Coarse-to-Fine Fabrication of Large 3D Objects*
[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*
[110] Beyer, D. et al. (2015) *Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates*
[108] Mueller, S. et al. (2014) *WirePrint: 3D Printed Previews for Fast Prototyping*

This is a reasonable approach for two key reasons:

- The focus on fabrication time and material usage (discussed further in Section 4.4.2) results in a deterministic problem – albeit one with many different variables that need to be explored. Consequentially, no variance in the simulation output can occur from repetition, and each simulation need only be run once (i.e. there is no need to investigate variance which is present with user studies or ones with stochastic elements).
- The initial prototype geometry is already in a digital file format (typically STL, commonly used in 3D printing). It follows that using computer simulations to manipulate and perform experiments on the geometry prevents unnecessary conversions between physical and digital domains and allows for rapid simulation runs.

The aim of this thesis is to solve the technical development of Hybrid Prototypes and investigate their potential benefits. While the use and impact on the design process are also factors, they are not covered in the research. Therefore, the cognitive aspects and physical affordances of user focussed prototyping is beyond the scope of the aim of this thesis making simulations a suitable experimental method.

Objects to Investigate

Prototyping efforts differ enormously depending on the design brief and the problems at hand. As a result, a generalisable prototype is difficult to define. Therefore, specific objects were used to fulfil the aim of this thesis. These acted as focal points for the implementation and characterisation of LEGO and 3D printing hybrid prototypes, from which more generalised comments and discussion could be drawn.

The investigation objects were chosen from *user–driven* products. Figure 4.3 shows the objects chosen to be investigated in the studies. The objects are as follows:

- Computer Mouse (Figure 4.3a)
- Video Game Controller (Figure 4.3b)
- Digital camera (Figure 4.3c)

These cover a range of sizes and complexities: from small and simple (the computer mouse) to larger with more features (the digital camera) – ensuring that Hybrid Prototyping can be investigated in different objects.

Although these objects include many small details (e.g. buttons, switches, textures) that have a function in the final product, the prototypes considered are purely form based with the design intent focussing on aesthetics, ergonomics and physical interaction. These prototypes allow designers (and stakeholders) to explore the shape and form of the product, how it feels to use and interact with it, and even reconfigure and change the layouts – all key activities in *proof–of–concept* prototypes.

(a) The computer mouse (b) The video game controller (c) The digital camera

Figure 4.3 The three objects used in the investigations

4.4.2 Metrics

As stated in Section 4.1, the aim of this thesis considers how LEGO and 3D printed Hybrid Prototypes can be used to lower the barriers to physical prototyping earlier in the design process. These barriers were found to be around the time it takes to create a prototype and the cost of materials and tools to do so. It follows that the two key metrics to investigate are:

- Fabrication Time – how long does it take to create the prototype?
- Material Usage – how much material is used to create the prototype?

Mueller *et al.* [54] introduced the concept of total fabrication time. This consists of two parts: the time to print the required parts, and the time to assemble the LEGO and printed parts. It would also be possible to consider the modification time as an aspect of the fabrication time of a prototype – i.e how long it takes to make a change to an existing prototype. Therefore the fabrication time used in this thesis is the time to print the necessary parts and then assemble the prototype together. The time to use the tool or to search for the required bricks are not included.

Material usage can be considered in two different ways. The direct approach is the amount of 3D printed parts and numbers of bricks are required to make a prototype. This is most easily measured by volume – i.e. the proportion (by volume) of 3D printed to LEGO parts of a prototype. However, the mass or material cost could also be used. The indirect approach is to use the level of reusability or reconfigurability of a prototype instance. This is a measure of how much of the current prototype can be used in a subsequent iteration (reconfigurability) or in another design (reusability). It can be more difficult to calculate as information about the next iteration or design is required for comparison. For the studies reported in this thesis, the reusability is the primary cost metric, however the absolute material use and reconfigurability are consider in the discussion.

These time and material metrics can be applied to both individual prototype instances or across multiple iterations, to measure the impact of Hybrid Prototypes. They also lend themselves to a simulation based approach to investigate Hybrid Prototypes as they can

[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*

be modelled and calculated computationally. For the fabrication time, the print times can be calculated using 3D print slicing software, such as Cura 3.6 [131], while the LEGO assembly rates can be calculated from empirical data. For the material usage, calculating the volume of complex 3D geometries can leverage software libraries, such as Blender (see Section 4.5.1). The calculations of these are covered in more detail in later chapters.

4.5 Technology Platform

This sections outlines the technology platform used to develop the hybrid prototyping tool for the purpose of this thesis. The development of the this tool was iterative and agile, taking place over the course of the research. The cyclical nature of the iterative development means there is not a natural point to introduce the technology platform within the linear narrative of the thesis. Therefore, the technology platform is covered here, before presenting the objectives in Section 4.6.1. Some elements are presented in this section are then discussed in more detail in later chapters.

The key requirements of the technology platform were:

- To enable the manipulation and creation of the geometry.
- To permit the investigation into multiple variables and permutations.
- To provide and understand the constraints of the physical techniques.
- To enable the physical construction of the resulting Hybrid Prototypes.

From these requirements, the technology platform was broken down into:

- Software – used to develop the logic and geometry manipulation of the Hybrid Prototyping tool.
- Hardware – used to physically embody the resulting prototype.

These two aspects are described in the following sections. While the concept of Hybrid Prototyping is applicable to many different prototyping techniques, the tools described here were used to explore and develop the coupling of LEGO and 3D printing. Consequently, these are not the only way to implement Hybrid Prototyping, and in fact different approaches would likely be taken if two other prototyping techniques were used.

4.5.1 Software

The software platform was chosen to enable the development of the Hybrid Prototyping tool. The reasons for choosing a computational based approach are discussed in Section 4.4. As a result, this required tools that could programmatically interact with digital 3D geometry and could create the logic that implements the coupling of LEGO and 3D printing. The tool was written in Python 3.7 programming language [132], as an add-on

[131] Ultimaker B.V. (2018) *Ultimaker Cura 3.6.0*
[132] Python Software Foundation. (2019) *Python 3.7*

that integrated into the 3D modelling software, Blender. Blender is introduced in more detail in the following section.

Blender

Blender [133] is a free and open source 3D creation suite. It supports the entirety of the 3D content creation pipeline: from modelling and animation, to simulation and rendering. However, only the 3D modelling features are required for the technology platform. Other 3D modellers such as Rhino 6 [134] or Autodesk 3DS Max [135] could have been used, however Blender 2.79 was used for two main reasons:

- It has an extensive and well-documented Python-based API that allows Blender's powerful functions (such as ray intersection, 3D volume calculations, Boolean operations on 3D objects) to be leveraged programmatically.
- It is well suited to handling mesh data, such as STL files, manipulating their geometry and ensuring that they can be 3D printed.

Furthermore, its native graphical user interface (GUI) could be used to interact with input objects and the resulting hybrid prototypes – allowing a more straightforward and intuitive user experience as a design tool. It also allows custom GUIs to be built that can provide input for the Hybrid Prototyping tool, and allow different parameters to be changed.

4.5.2 Hardware

The physical hardware used in demonstrating the case studies consisted of commercially available LEGO pieces and low cost 3D printers. The following sections give a brief overview of these two aspects.

LEGO

LEGO is a block based construction kit, originally designed as a children's toy. The variety and quantity of elements within LEGO construction kits has increased substantially since its initial introduction. The current count of unique elements stands at over 5,000 and are available in a wide variety of colours. At its core, LEGO comprises of different sized cuboid bricks (see Figure 4.4) that can be combined in countless ways [136]. To increase the fidelity of LEGO models, a large number of specialised elements exist, some which are curved or sloped, or more have more specific uses such as doors, windows, and wheels. As the desired fidelity increases, the requirement for specialised elements increases, however the range of sizes of these elements is limited – restricting their use outside of situations where their scale matches the desired geometry. Consequentially, the LEGO bricks considered in this thesis will be the standard cuboid ones.

LEGO bricks employ a *stud–and–tube* based interface that allows the bricks to connect to

[133] Blender Foundation. (2018) *Blender 2.79*
[134] McNeel Europe. (2018) *Rhino 6*
[135] Autodesk Inc. (2019) *Autodesk 3DS Max 2019*
[136] Gopsill, J. (2018) *Examining the Solution Bias of Construction Kits*

each other using the clutch of an interference fit. However, this interface exists only on the top and bottom faces of the bricks forcing there to be only one possible build plane. This can be broken with specialised right-angled pieces or advanced techniques that can adapt the build direction [113], however these complicate the generation and assembly of models and so are not considered.

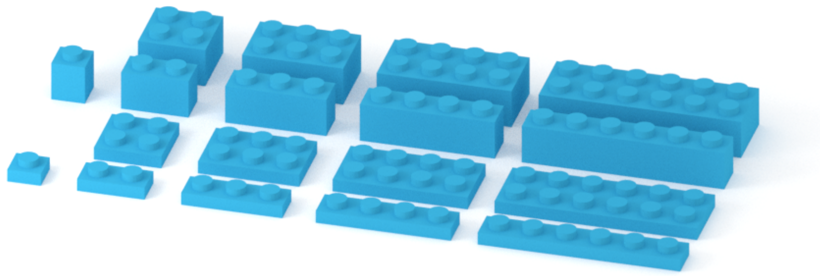


Figure 4.4 The library of standard LEGO bricks

The smallest LEGO brick, known as a 1×1 plate, measures 8 × 8 × 3.2 mm. The rest of the LEGO bricks in the standard library (shown in Figure 4.4) can be made from discrete numbers of 1×1 plates. For example, a 2×1 brick is equivalent to six 1×1 plates. However, this property only applies to the standard cuboid LEGO bricks and not the more specialised elements. This combinatorial property is another key reason for limiting the LEGO bricks to those in the standard library. The benefits and limitations of using the standard library of bricks is discussed further in Section 9.4.

3D Printing

The 3D printers used over the course of this research were Ultimaker 2+ [137]. These are part of the filament deposition modelling (FDM) family of printers that create objects by extruding and depositing thermoplastic material along a pre-determined path layer-by-layer. Figure 4.5 illustrates the FDM printing process.

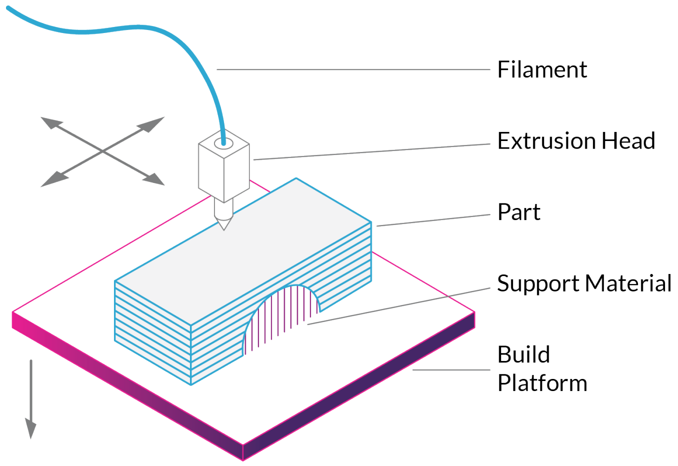


Figure 4.5 An illustration of the FDM printing process

[113] Enjary, D. (2007) *The Unofficial LEGO Advanced Building Techniques Guide*
[137] Ultimaker B.V. (2019) *Ultimaker 2+*

The Ultimaker 2+ printer has X, Y, Z resolutions of 12.5, 12.5 and 5 µm respectively [137] - equating to achievable layer heights of 0.02 mm. This level of precision is sufficient to 3D print LEGO compatible parts that can adequately interface with commercially injection moulded bricks. However, geometry of the printed interface had to be redesigned to ensure a better and more reliable fit. The redesigned interface is explained in more detail in Section 6.5.4

Optimising FDM 3D printing for print speed is out of scope for this thesis – there are many variables to consider, including layer-height, sparse infill percentage and head movement speeds, all of which can have significant impact on the print time (and output quality). As *looks-like* prototypes only need to be strong enough to be handled, the recommended infill percentage is between 10–20 %. Alteration within this range will not drastically alter the print time [138]. Therefore, the print settings were kept constant for all of the studies at: 0.15 mm layer height, 18 % infill, and 60 mm/s print speed.

4.6 Research Plan

This section outlines the research plan, embodied as objectives and how these objectives fit into the thesis structure.

4.6.1 Objectives

The research questions established in Section 4.2 were broken down into specific objectives that could be achieved over the course of the research. These objectives are outlined in Table 4.1, along with which research questions they answer.

Table 4.1 The thesis objectives and how they relate to the research questions

No.	Objective	RQs
1	Establish & implement technology platform and method	1, 2, 3
2	Implement simulation experimentation	1
3	Characterise theoretical benefits	1
4	Establish requirements and method for practical implementation	2
5	Implement practical method	2
6	Establish strategies to optimise practical benefits	3
7	Investigate & characterise strategies for maximising benefits	3
8	Characterise & demonstrate benefits in case studies	1, 2, 3

Objectives 1 and 8 are higher level objectives that span all three research questions, and are revisited throughout the course of the research. The first objective considers the development and implementation of the algorithms and software tool for Hybrid Prototyping, while the last objective involves the use of case studies to demonstrate the benefits of HP.

[138] Álvarez, K. et al. (2016) *Investigating the influence of infill percentage on the mechanical properties of fused deposition modelled ABS parts*

Research question 1 is answered by Objectives 2 and 3. The second objective is to implement the simulation experimentation, with the third objective characterising the results from the simulation study.

Objectives 4 and 5 answer Research Question 2. The fourth objective develops the requirements and methods for practically implementing HP. These are then demonstrated in the fifth objective.

Finally, Research Question 3 is answered by Objectives 6 and 7. The sixth objective looks to develop strategies to improve and maximise the practical benefits of HP. The selection, investigation and characterisation of these strategies are considered in the seventh objective.

4.6.2 Thesis Structure

This section takes the Research Questions (established in Section 4.2) and the objectives (established in Section 4.6.1) and maps them to the chapters of the thesis. This is illustrated in Figure 4.6: showing the structure of the thesis with a brief summary of each chapter.

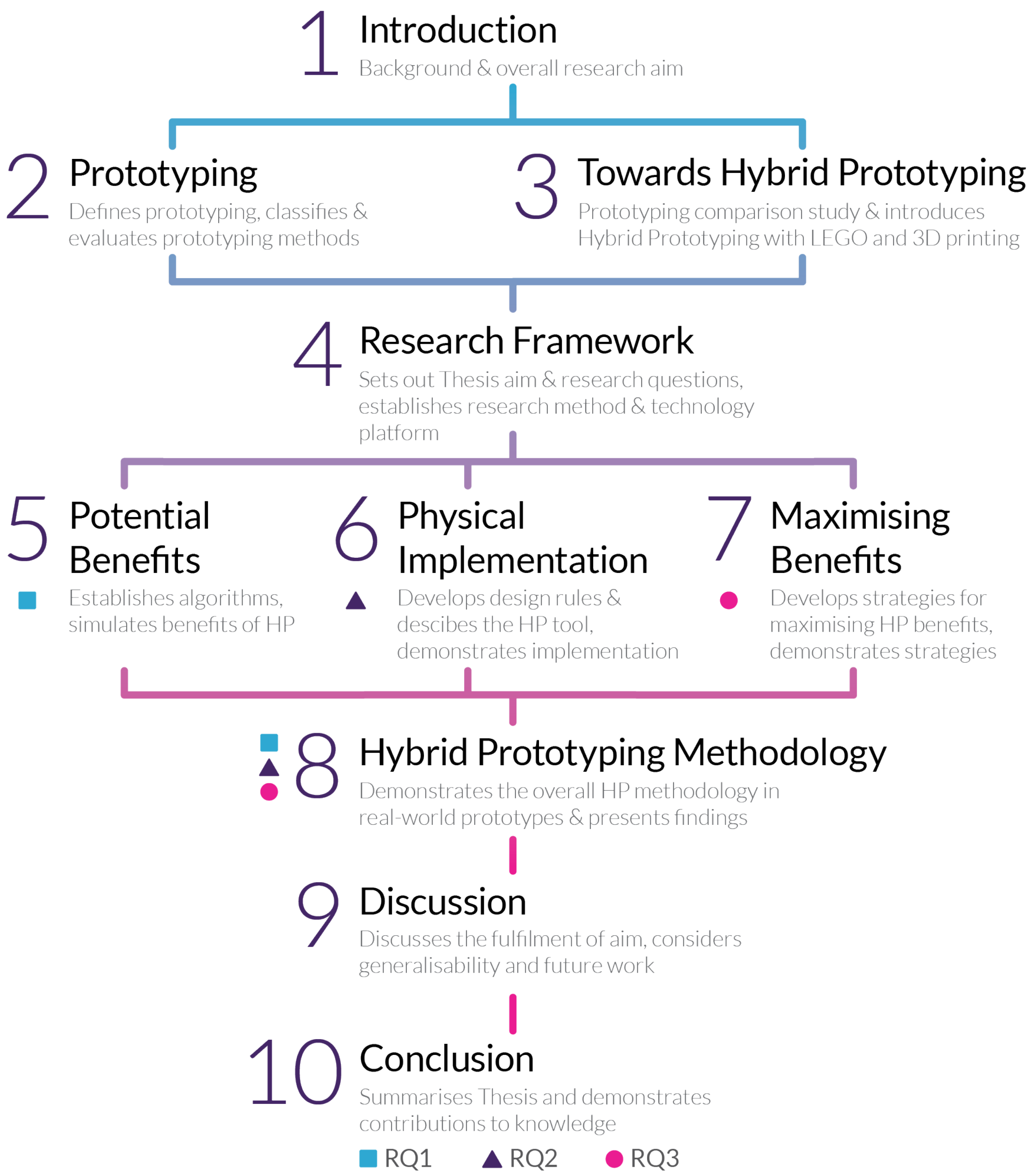


Figure 4.6 The structure and chapter break down of the thesis

Chapter 5

Potential Improvements

5.1 Overview

As discussed in Chapter 4, a simulation based approach was chosen to investigate the coupling of 3D printing and LEGO. Through establishing the potential benefits of such a coupling, the first research question can be answered. The first research question is:

> "RQ1: What are the potential time and material savings from Hybrid Prototyping?"

The characterisation of the potential benefits in time and material savings act as target metrics for the later chapters in this thesis.

The large number of variables and complexity of the geometry in the chosen case studies lend themselves to a computational approach that allow many combinations of the variables to be calculated quickly. The use of simulation permits the investigation and characterisation of Hybrid Prototyping, and the practicalities of implementing such a prototyping method are explored in Chapter 6.

This chapter starts by describing the underlying algorithms applied during the development and investigation of the Hybrid Prototyping tool. Following this, a simulation study is reported that investigates the potential benefits to fabrication time and reusability; across six primitive objects, and 50 different sizes. The chapter concludes with a discussion of the results and how the first research question has been answered.

5.2 Simulation Based Approach

This section will cover the core algorithms that form the basis of the simulations performed in this thesis. These algorithms are developed further in subsequent chapters as the Hybrid Prototyping tool is developed, with the changes described at the appropriate points.

To give context to these algorithms, the overall approach to coupling LEGO and 3D printing for Hybrid Prototyping uses LEGO to occupy the internal volume of a prototype, with 3D printing providing high-fidelity surfaces to attach onto the LEGO. There are close parallels with CNC machining where the LEGO is a 'rough cut' – forming the quick, approximate shape, and the 3D printing is a 'finishing pass' — creating high fidelity detail more slowly.

In order to achieve this, the required number and locations of LEGO bricks need to be calculated and the remaining geometry to be printed must be generated. There are three main algorithms that perform the tasks. They are as follows:

1. *Brixellation* – calculates the intersections between an array of bricks and the prototype geometry through ray casting.
2. *Packing* – calculates the LEGO structure and list of required bricks through the use of a first-fit decreasing bin-packing algorithm.

3. *Shelling* – generates the outer geometry shell that is to be 3D printed by calculating the difference between the original geometry and the LEGO bricks.

Figure 5.1 shows a flow diagram of how these algorithms are used in simulating the potential benefits of Hybrid Prototyping.

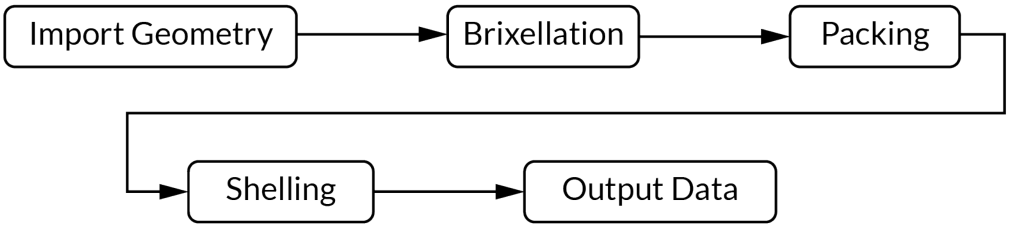


Figure 5.1 The overall algorithm process for simulating the potential benefits

5.2.1 Brixellation Algorithm

The Brixellation algorithm generates the locations of 'base' bricks inside the prototype geometry. The 'base' brick leverages an intrinsic property of LEGO and other block based construction kits: the larger bricks can be made from an integer number of the smallest bricks. In the case of LEGO, the smallest bricks are 1×1 plates that measure $8 \times 8 \times 3.2$ mm. Using this property allows an array of the smallest bricks to be calculated that can be optimised with larger bricks later (see Section 5.2.2).

In order to generate the locations of bricks inside the object, the bricks' intersections with the prototype geometry need to be calculated. The calculation algorithm employed is a variant of the discrete voxel approach described by Nooruddin and Turk [139]; using parity count ray casts to determine whether a point is inside an object or not. An alternative to parity count ray casting would be to use bounding volume hierarchy (BVH) trees to calculate if two 3D geometric objects intersect. However, the increased computational overhead of BVH Trees outweighed the benefits of a more accurate intersection calculation.

Parity count ray casting involves taking a point and casting a ray in a direction from the point. The number of times the ray intersects with the target geometry are counted. Equation 5.1 shows how the parity of the intersection count, N, determines whether the point is inside the geometry.

$$\text{Inside} \equiv \begin{cases} \text{True} & \text{if } N \text{ is odd} \\ \text{False} & \text{if } N \text{ is even} \end{cases} \tag{5.1}$$

Figure 5.2 illustrates Equation 5.1 with two exemplar points and four potential rays. It is important that the rays are cast far enough to ensure they are long enough to pass

[139] Nooruddin, F. S. and Turk, G. (2003) *Simplification and repair of polygonal models using volumetric techniques*

through the object, similarly the origin point must not be too far from the object. Furthermore, the target geometry must be a manifold, closed surface for the parity count to be valid. Generally, one ray is sufficient to check whether the point is inside the object, however there are edge cases that could result in false positives. For example, an outside point with a ray that intersects at a tangent to the target object – resulting in one intersection (odd) and the determination of the point being inside.

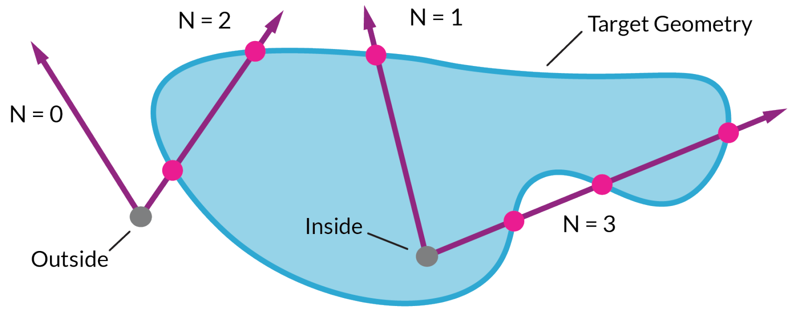


Figure 5.2 An illustration of using parity count ray casting to determine whether a point is inside an object

As this algorithm is focussing on LEGO bricks that occupy space, these edges cases can be mitigated and the reliability of the output improved by using multiple points on the brick with multiple rays from each point. This was achieved by casting rays along each of the edges of a brick (ignoring the stud) and casting six orthogonal rays from the centre of the brick.

The ray casting leveraged the `ray_cast` function built into the Blender 2.79 API [140] that casts a ray from a point in a particular direction for a certain distance. The function returns whether an object was hit and the hit location.

Using these multiple rays it is possible to calculate if a LEGO brick at any arbitrary point is inside the target geometry. Three classifications of intersection could be identified:

- Inside – a brick fully inside the 3D object.
- Boundary – a brick that intersects with the surface of the 3D object.
- Outside – a brick fully outside the 3D object.

These classifications are illustrated with a 2D array of bricks in Figure 5.3.

An empty 3D array, A of size $I \times J \times K$, was generated using the base brick dimensions and object bounding box dimensions, as shown in Equation 5.2. Equivalent to the integer number of bricks required to meet the dimensions. Where $[W\ D\ H]$ are the dimensions of bounding box and $[w\ d\ h]$ are the dimensions of the brick.

$$I = \left\lceil \frac{W}{w} \right\rceil \qquad J = \left\lceil \frac{D}{d} \right\rceil \qquad K = \left\lceil \frac{H}{h} \right\rceil \tag{5.2}$$

Each element represents a brick, B_{ijk}, in real space. Using a known start position, $\vec{s}$, each individual brick can be described by a series of coordinates and a vector, $\vec{b}$, to its origin

[140] Blender Foundation *Blender 2.79 API Documentation*

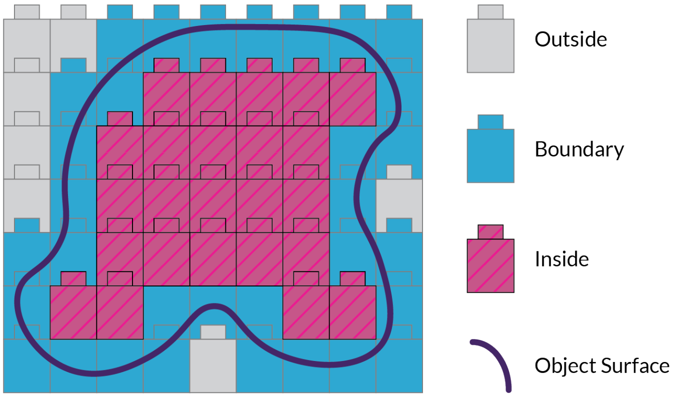


Figure 5.3 A 2D illustration of the three levels of brick intersection

in real space so that it can be related to the target 3D geometry. $\vec{b}$ and $\vec{s}$ are shown in Equation 5.3.

$$\vec{b} = \begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix} \qquad \vec{s} = \begin{bmatrix} x_s \\ y_s \\ z_s \end{bmatrix} \qquad (x, y, z) \in \mathbb{R}^3 \tag{5.3}$$

From this, it is possible to define the position of any brick, $B_{i\,j\,k}$, from the array indices of A, as shown in Equation 5.4.

$$B_{i\,j\,k} = \vec{b} = \begin{bmatrix} i-1 \\ j-1 \\ k-1 \end{bmatrix} \begin{bmatrix} w & d & h \end{bmatrix} + \vec{s} \qquad \begin{matrix} (i = 1, 2, \ldots, I), \\ (j = 1, 2, \ldots, J), \\ (k = 1, 2, \ldots, K) \end{matrix} \tag{5.4}$$

For each element, the brick intersection was calculated and array, A, populated with the binary results. Equation 5.5 shows how the brick intersection array was generated.

$$A_{i\,j\,k} = \begin{cases} 1 & \text{if } B_{ijk} \text{ inside} \\ 0 & \text{else} \end{cases} \qquad \begin{matrix} (i = 1, 2, \ldots, I), \\ (j = 1, 2, \ldots, J), \\ (k = 1, 2, \ldots, K) \end{matrix} \tag{5.5}$$

The output of this algorithm is a binary intersection array that is a voxelisation of the target geometry using the dimensions of the base brick.

5.2.2 Packing Algorithm

From Brixellation, all the positions for the base bricks can be found, however this results in the most bricks required to construct the prototype. Due to the intrinsic property of block based construction kits (see Section 5.2.1), it is possible to reduce the brick count by packing larger bricks into the array. This could be achieved as there are standard libraries of bricks that are discrete combinations of the base brick. The justification for using the standard bricks was discussed in Chapter 4, however this combinatorial property was one of the key considerations. The brick packing algorithm was applied to combine the bricks in the 3D intersection array into bricks from the standard library as shown in Figure 5.4.

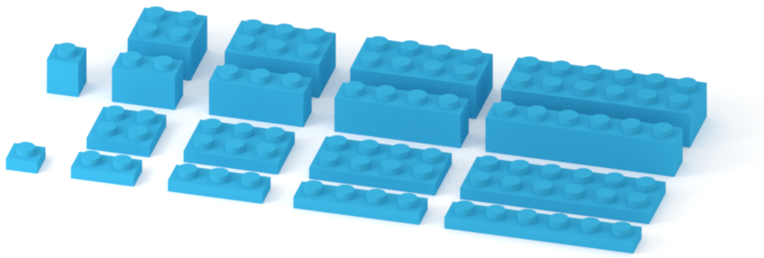


Figure 5.4 The standard library of LEGO bricks.

Using the dimensions of the set of bricks shown in Table A.2, a greedy first-fit decreasing algorithm was used that tried to fit the largest brick (i.e. a 2×6 LEGO brick) down to the smallest (i.e. a 2×1 LEGO plate). The library of bricks, L, was ordered using the brick's volume following the condition shown in Equation 5.6.

$$\prod_{m=1}^{3} L_{n\,m} \geq \prod_{m=1}^{3} L_{n+1\,m} \qquad (n = 1, 2, \ldots, |L|) \tag{5.6}$$

This resulted in an decreasing list that started with the largest brick (by volume) and ended with the smallest.

For each in brick, L_n, in the library, the brick packing algorithm attempts to fit it in the voxel array, A, by using each element, $A_{i\,j\,k}$, as the starting point for the condition criteria shown in Equation 5.7. This algorithm is greedy - fitting the brick at the first possible opportunity without consideration for how the packing could be optimised.

$$\sum_{a=0}^{L_{n\,1}} \sum_{b=0}^{L_{n\,2}} \sum_{c=0}^{L_{n\,3}} A_{i+a\,j+b\,k+c} = \prod_{m=1}^{3} L_{n\,m} \qquad \begin{array}{l} (n = 1, 2, \ldots, |L|), \\ (i = 1, 2, \ldots, I), \\ (j = 1, 2, \ldots, J), \\ (k = 1, 2, \ldots, K) \end{array} \tag{5.7}$$

Once the brick has been tried at each position, the next brick is selected. Before decreasing the brick size, the brick is rotated 90 degrees to test if it fitted in an orthogonal direction. This bin-packing process was repeated until no more bricks could be fitted.

No optimisations of brick packing arrangement are performed at this point. While optimising for layout, strength and minimum number of bricks are important from a practical perspective, for the simulation studies described later in this chapter the results reflect the limits, and hence bounds on potential benefits of hybrid prototyping. As a consequence, optimisation is not required at this stage. Furthermore, performing these optimisations is computationally expensive due to the large number of possible brick arrangements [136]. As such, it is possible that a different algorithm may be required.

[136] Gopsill, J. (2018) *Examining the Solution Bias of Construction Kits*

5.2.3 Shelling Algorithm

The Shelling algorithm generates the geometry of the prototypes parts that are to be 3D printed. The overall approach is to calculate the difference between all of the LEGO bricks (output from the brick packing, see Section 5.2.2) and the original geometry, this is shown in Equation 5.8.

$$R_g = O_g - \bigcup_{n \in B} B_n \tag{5.8}$$

Where R_g is the resultant geometry, O_g is the original geometry, and B is the list of bricks to be used to construct the prototype, with B_n representing each brick.

The geometry generation leverages Blender's built-in 3D Boolean operations [140] that allow the easy union, intersection and difference of two objects. Equation 5.8 is the result of the difference between the original geometry and the union of all the bricks. This is illustrated in Figure 5.5 in a 2D case.

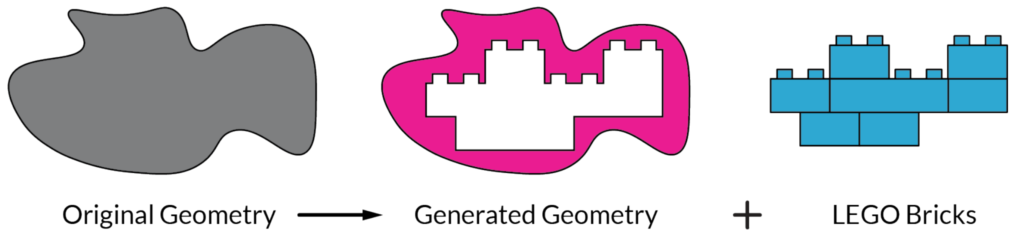


Figure 5.5 A 2D illustration showing the geometry generated for 3D printing

The resultant geometry is a hollow shell, suitable for the simulation study described in Section 5.3 as the parts do not need to be printed. However, the hollow shell would need to be decomposed into printable parts to be practically implemented. Consequentially, two aspects of the geometry generation are not considered in this section:

- The location of cut planes and their use to separate the resultant geometry into 3D printable parts.
- The generation of the interfaces between the LEGO and 3D printed parts.

These are required to ensure that the prototypes can be fabricated, and so they are explained in the development of the practical implementation of Hybrid Prototyping in Chapter 6.

5.3 Simulating Benefits

As set out by Research Question 1, the potential benefits around reduced fabrication time and material savings need to be investigated for Hybrid Prototyping. Therefore, the two key metrics that were investigated in the study were the total fabrication time and the reusability of a prototype. Table 5.1 explains the importance and benefits of studying these two metrics.

[140] Blender Foundation *Blender 2.79 API Documentation*

Table 5.1 The definitions of the simulation study metrics

Metric	Definition
Fabrication Time	The length of time it takes to fabricate a prototype
Reusability	The ability to reuse or edit parts of a prototype

The importance of these two metrics are:

- A shorter fabrication time leads to more prototyping through faster, compressed, design iterations influencing learning and the quality of the final product. It also reduces product development costs.
- A reusable prototype reduces material wastage, improves resource utilisation and speeds up fabrication, and supports thinking-speed exploration of design alternatives. High reusability enables rapid modification and lower material costs.

The metric of reusability considers how much of a prototype instance can be reused or reconfigured into another prototype instance. Here the reusability is a proxy for the material costs, with a higher reusability giving rise to lower material costs. The assumption in this study was that only the bricks can be reconfigured into a new prototype iteration while none of the 3D printed parts could be reused. However, in practice it is possible that some of the 3D printed parts could be reconfigured and reused between iterations.

The study described in the following sections was first reported by the author in Design Studies, Vol. 62 [1], and has been built upon for this thesis.

5.3.1 Method

The overall method employed for this study was to measure the affect of changing key variables on the metrics identified at the start of this section. The simulations were run over 50 object sizes for each of the six primitive geometries using the three sizes of brick. These variables are explained in more detail in Section 5.3.1. The overall process for the simulation runs is shown in Figure 5.6.

An illustrative case study was also investigated to show the potential benefits of Hybrid Prototyping over multiple iterations.

Variables

There are several different variables that could be considered when investigating Hybrid Prototyping methods. At a high level these include; prototype design purpose, level of prototype functionality, and complexity of objects. However, these are challenging to measure and difficult to simulate in a robust and repeatable manner. In order to characterise the initial Hybrid Prototypes, three key independent variables were identified: the object shapes, size of the objects, and the sizes of bricks. This permitted the HPs to be investigated over a series of controlled situations. A corollary variable that related the size

[1] Mathias, D. et al. (2019) *Accelerating product prototyping through hybrid methods: Coupling 3D printing and LEGO*

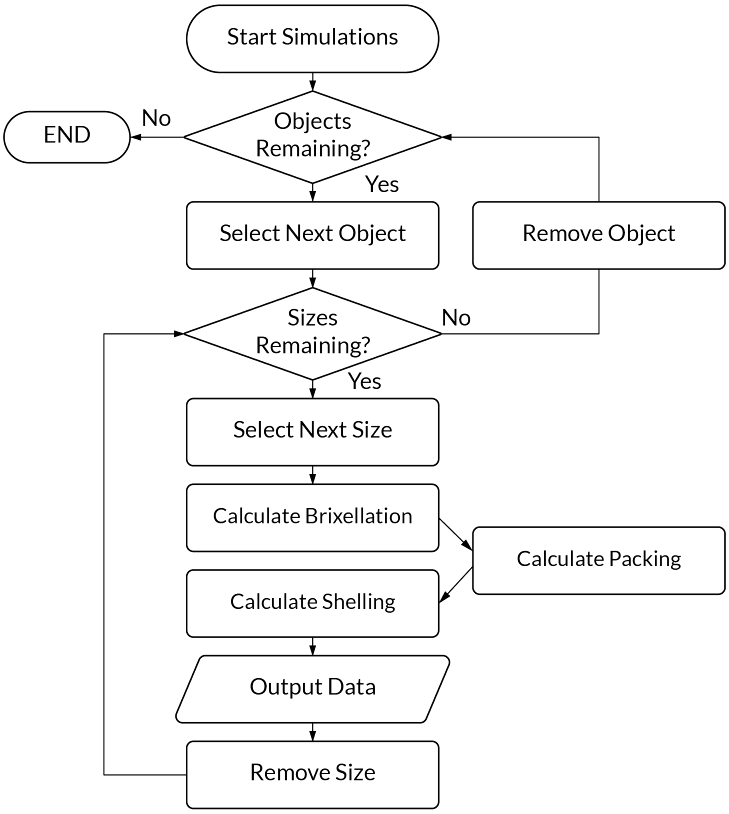


Figure 5.6 A flow diagram of the overall simulation process

of objects to the size of the bricks was also used. Table 5.2 shows the four variables that were chosen to investigate the metrics in the simulations. These variables are described in more detail later in this section.

Table 5.2 The simulation variables, their descriptions and the values used

Variable	Description	Values
Object Geometry	The 3D geometry of the object	Cube, Cylinder, Cone, Sphere, Tetrahedron and Triangular Prism
Object Size	The volume of the object	1×10^3 to 8×10^6 mm^3
Construction Kits	The different scales of construction kit used	NANO Blocks, LEGO, DUPLO
Brick-to-Object Ratio	Normalised ratio of brick to object volume	$0 < r \leq 1$, where 1 would be using a brick the same volume as the object

Object Geometry

The object geometries chosen for the simulation runs were taken from Constructive Solid Geometry (CSG) Modelling [141]. The primary axiom of CSG Modelling is that any shape can be generated through the combination of simple primitives, and thus these primitives are justified as the base objects for the construction of any form-based

[141] Requicha, A and Voelcker, H. (1977) *Constructive Solid Geometry*

prototype. These primitives consisted of: Cube, Cylinder, Cone, Sphere, Tetrahedron and Triangular Prism. Figure 5.7 shows the six different primitives.

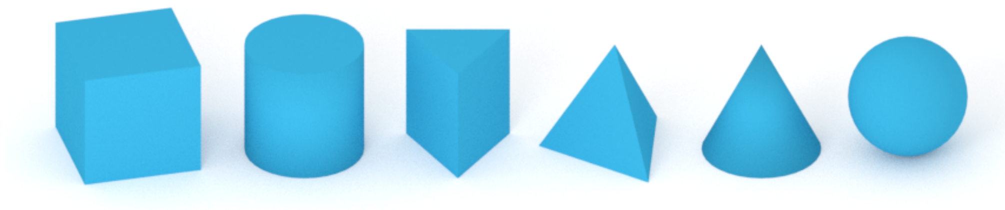


Figure 5.7 The primitive shapes used in the simulations. From L to R: Cube, Cylinder, Triangular Prism, Tetrahedron, Cone, and Sphere

The use of primitive geometries covered most types of geometry that are found in more complex designs: planar surfaces (Cube, Tetrahedron, Triangular Prism), orthogonal geometry (Cube, Cylinder, Triangular Prism), non-orthogonal (Tetrahedron, Triangular Prism), single curvature surfaces (Cylinder, Cone) and double curvature surfaces (Sphere). As this thesis is investigating coupling 3D printing and construction kits more generally and these geometries are frequently combined into more complex shapes, the results presented do not consider the primitives individually. Instead, the median is calculated from the results of the simulations for all six primitives.

Object Size

It is expected that different sizes of object could have differing levels of benefit from Hybrid Prototyping, depending on the ratio of prototype size to the brick size. As such that there will likely be a trade-off between reusability and fabrication time for ratios of object to brick sizes.

The ratio of object to brick size was initially described by keeping the construction kit size fixed and varying the object size. The volume of the objects was varied over a range of 1×10^3 to 8×10^6 mm^3. These volumes were used as they are within the bounds of feasibility for most commercially available desktop low cost 3D printers – such as the Ultimaker 3 (9.42×10^6 mm^3 [137]) and Makerbot Replicator+ (9.45×10^6 mm^3 [142]). The simulations were stepped 50 times over this volume range. This was then repeated for each of the object shapes, and each of the sizes of brick.

Construction Kits

By changing the relative size of the bricks with the object, the effect of scale on fabrication times and reusability could be explored. The initial brick size was LEGO with dimensions of $8 \times 8 \times 3.2$ mm. For these simulations, a pool of standard bricks could be used to reduce the overall brick count (see Brick Packing, Section 5.2.2). Smaller and larger bricks were considered either side of LEGO, these include NANO ($4 \times 4 \times 3.2$ mm)

[137] Ultimaker B.V. (2019) *Ultimaker 2+*
[142] MakerBot Industries. (2018) *MakerBot Replicator +*

and DUPLO ($16 \times 16 \times 19.2$ mm). The use of different sizes of brick affords different levels of fidelity, with the expectation that the smaller bricks will allow a better approximation of more complex geometry. For the purposes of this study a continuum of brick sizes is considered, with the three instances of NANO, LEGO and DUPLO used as reference points.

Normalised Brick-to-Object Ratios

There are issues associated with matching object dimensions to the limited availability of brick sizes. This can be addressed by generating a brick-to-object size ratio. It affords more robust comparisons between the primitive shapes and a better insight into how the ratio between brick volume and object volume affects the level of reusability and fabrication time. In the simulations using these ratios, the object size is fixed, and a hypothetical brick size is created using the brick-to-object ratio. The brick-to-object ratios ranged from 1:10,000 to 1:100.

Data Collected

In order to calculate Equations 1-4, three values were recorded for each simulation:

- V_o – Volume of the object
- V_B – Volume of all the bricks
- N_B – Brick count, including the overall count and each of the different brick types.

The volume of the object was calculated using Equations 5.9 and 5.10 [143].

$$V_i = \frac{1}{6}(v_1 \times v_2) \cdot v_3 \tag{5.9}$$

$$V_{\text{total}} = \sum_{i \in V} V_i \tag{5.10}$$

Where v_1, v_2, v_3 are the vertices of each triangular face of the object.

The volume of the LEGO bricks was the simple summation of the cuboid volumes of each of the bricks used. To get the overall brick count, the numbers of each brick type were summed together.

Calculation of Metrics

This section describes the calculations performed to generate the fabrication time and reusability from the data collected (see Section 5.3.1). Part of these calculations required some empirical data to be collected: 3D print rate estimation, and brick assembly rate.

Optimising FDM 3D printing for print speed is out of scope for this thesis – there are many variables to consider, including layer-height, sparse infill percentage and head movement speeds, all of which can have significant impact on the print time (and output quality). As *looks-like* prototypes only need to be strong enough to be handled, the recommended infill percentage is between 10–20 %. Alteration within this range will not

[143] Zhang, C. and Chen, T. (2001) *Efficient feature extraction for 2D/3D objects in mesh representation*

drastically alter the print time [138]. Therefore, the print settings were kept constant at: 0.15 mm layer height, 18 % infill, and 60 mm/s print speed.

The print time per unit volume was estimated by calculating the print time for a range of different objects. Figure 5.8 shows the relationship between the volume of different shapes and their respective print times. Mueller *et al.* [54] state that 3D print times are mostly related to volume of the object being printed. Therefore, for a general estimate of Print Rate it is possible to fit a linear relationship function. The Print Rate, R_p, as time per unit volume, was found to be 8.328×10^{-2} s/mm^3. This results in an equivalent volume build rate of 12.01 mm^3/s, which is 75 % of the maximum material deposition of 16 mm^3/s the Ultimaker 2+ [137]. Which is as expected as the infill was not set at 100 % meaning less material was required to print the objects.

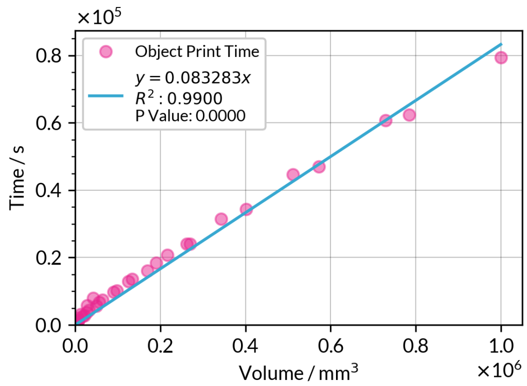


Figure 5.8 The relationship between object volume and print time

There was no existing literature or sources on average LEGO brick assembly rates. Therefore, the assembly time per brick had to be estimated experimentally. 14 participants built a small model out of 17 LEGO bricks, and their times recorded. Table 5.3 shows the results from this experiment and shows that the Assembly Rate, R_a, as time per brick, is 18.33 s/brick. One assumption that has been made is that the assembly rate is independent of the size of brick.

Table 5.3 Experimental results for brick assembly rates

Participants	Mean / s	SD / s	Assembly Rate / s/brick
14	311.58	60.84	18.33

[138] Álvarez, K. et al. (2016) *Investigating the influence of infill percentage on the mechanical properties of fused deposition modelled ABS parts*
[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*
[137] Ultimaker B.V. (2019) *Ultimaker 2+*

Fabrication Time

The following equations were used to calculate the total fabrication time, T_f, of the prototype.

$$T_p = (V_o - V_B) \cdot R_p \tag{5.11}$$

$$T_a = N_B \cdot R_a \tag{5.12}$$

$$T_f = T_p + T_a \tag{5.13}$$

where T_p is the print time, T_a is the assembly time, V_o and V_B are the volumes of the object and bricks respectively, N_B is the number of bricks, and R_p and R_a are the print and assembly rates.

Reusability

The measure of reusability was based on the volume of the object geometry. The mass of the resultant prototype was difficult to estimate as the building blocks and 3D printed parts will have different densities (and be dependent on the print settings used). As a result, it is difficult to calculate the reusability based on mass. Correspondingly, a volume-based approach is adopted for comparisons between prototype iterations. This was measured as the proportion of the object that was constructed from construction kit bricks, expressed as a percentage. Equation 5.14 shows the calculation.

$$P = \frac{V_B}{V_o} \times 100 \tag{5.14}$$

Where P is the brick proportion percentage, V_o is the volume of the object, and V_B is the volume of all the bricks used.

Case Study

While the primitive objects show how Hybrid Prototyping can handle different geometric features, these are rarely found in isolation in real-world objects. To illustrate the benefits of coupling 3D printing and LEGO when prototyping a design, four iterations of the design for a video game controller were simulated. The aim is to show how the benefits can compound over multiple iterations. Figure 5.9 shows the four design iterations with increasing details and geometric complexity as the design progresses. For this case study, the brick size was kept constant, using the LEGO as the brick size in the simulations for each of the iterations.

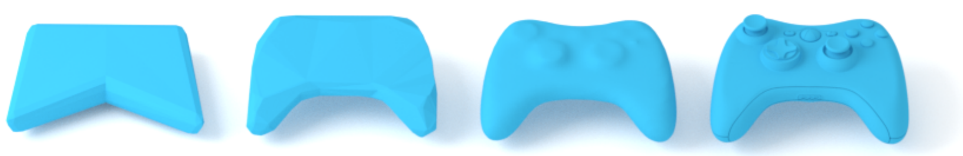


Figure 5.9 Video game controller design iterations 1-4, increasing in detail from left to right

5.3.2 Results

The results of the simulation study have been broken down into three sections: fabrication time, reusability, and the iterative case study. Each described in the following sections.

Fabrication Time

Figure 5.10 shows the simulation results of total fabrication time (brick assembly time + shell print time) against object volume. A reference line for 3D printing the entire object is also plotted. As can be seen, there is a significant difference between the total fabrication time for the three sizes of bricks. The use of NANO bricks resulted in a slower fabrication time than just printing the object. While coupling with LEGO bricks saw the greatest improvement in fabrication time. However, it is apparent that there is a trade off between brick size and object volume – with the larger DUPLO bricks performing worse than the LEGO.

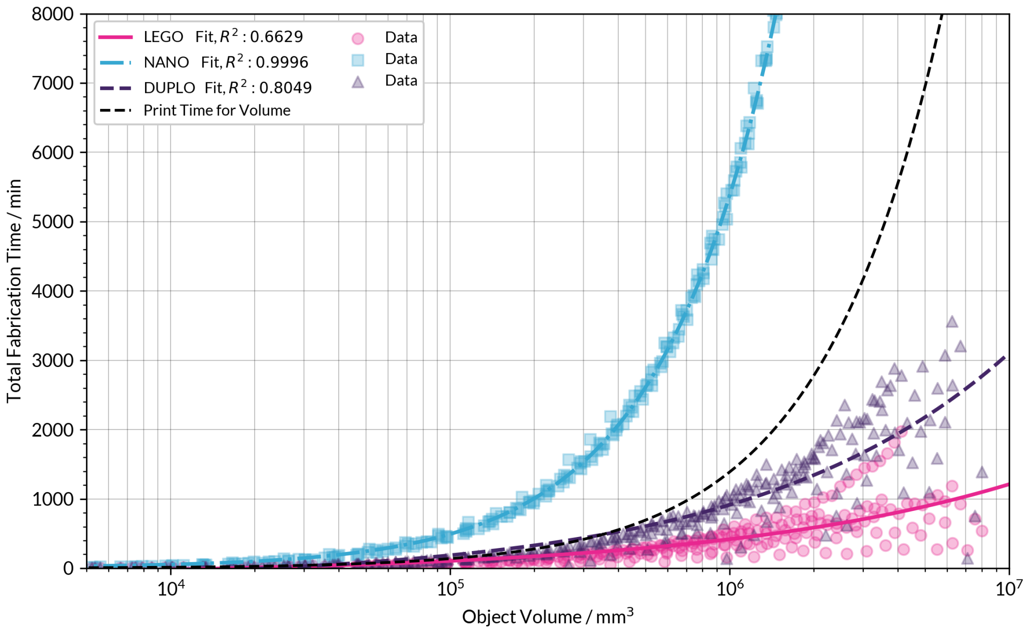


Figure 5.10 The total fabrication time against the object volume for the three brick sizes, a reference line for solely printing the object is included

This trade off was investigated further by adjusting the simulations to run varying brick sizes against fixed sized objects giving a continuous brick-to-object ratio between 1:10,000 to 1:100. The resulting fabrication time was normalised against the time it would take to 3D print the entire object. These simulations were run on the same six primitives over a range of 200 brick-to-object ratios. Furthermore, successive simulations of each primitive in different orientations were performed to avoid any potential issues where the orientation could affect the results.

Figure 5.11 shows the median and interquartile range of the fabrication time difference for the range of brick-to-object ratios simulated. For the size and dimensions of the

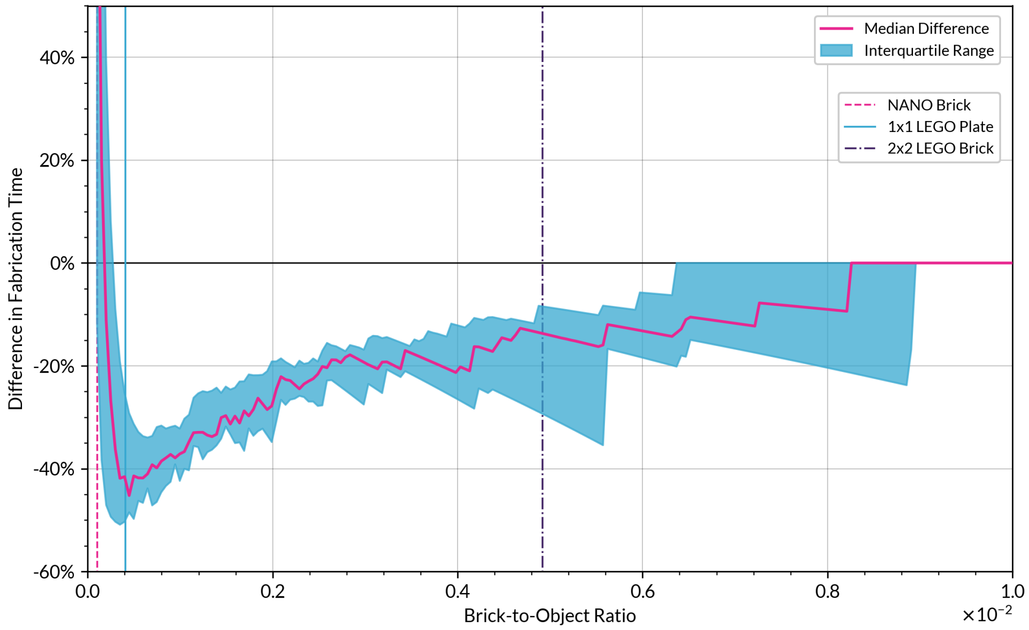


Figure 5.11 The difference in fabrication time against brick-to-object ratio. Reference ratios are also shown

primitives used, reference points of NANO and LEGO bricks are shown to contextualise the findings (DUPLO bricks are beyond the data range plotted). It shows that as the brick-to-object ratio gets smaller (i.e. smaller bricks for the same object) the fabrication time becomes shorter, until the ratio is too small (i.e. very small bricks) when the fabrication time rapidly rises above that of 3D printing the entire object due to the increased assembly time. The step changes in time difference arise from packing bricks of one discrete size into a fixed 3D form followed by bricks of a slightly larger size. In some cases, the bricks fit well, occupying most of the space (larger reduction in fabrication time due to less printing), then a small change in brick size means that they cannot pack as many in (smaller reduction in fabrication time due to a larger proportion being printed).

Reusability

Figure 5.12 shows the reusability (measured as brick proportion percentage – see Equation 5.14) against the object volume for the three brick sizes. As expected, when the object size increases the approximation of the geometry improved across all the brick sizes used. NANO Bricks performed the best, and DUPLO the worst. This implied that using smaller bricks (compared to object size) would result in a greater proportion of the prototype constructed from bricks and so have a greater level of reusability.

As in Figure 5.11, the six primitives were used over the 200 ratios. Figure 5.13 shows the median and interquartile range of the brick proportion percentage for each of these ratios. For the size and dimensions of the primitives used, reference points of NANO and LEGO bricks are shown to contextualise the findings (DUPLO bricks are beyond the data range plotted).

This confirmed the findings from the initial simulations in Figure 5.12 – that as the brick-to-object ratio decreases (object gets bigger, or bricks get smaller) then the brick proportion tends to 100%. This, therefore, means that the level of reusability is higher, and less material is required to print the remainder of the object. To create a more reusable prototype the brick-to-object ratio must be as small as possible.

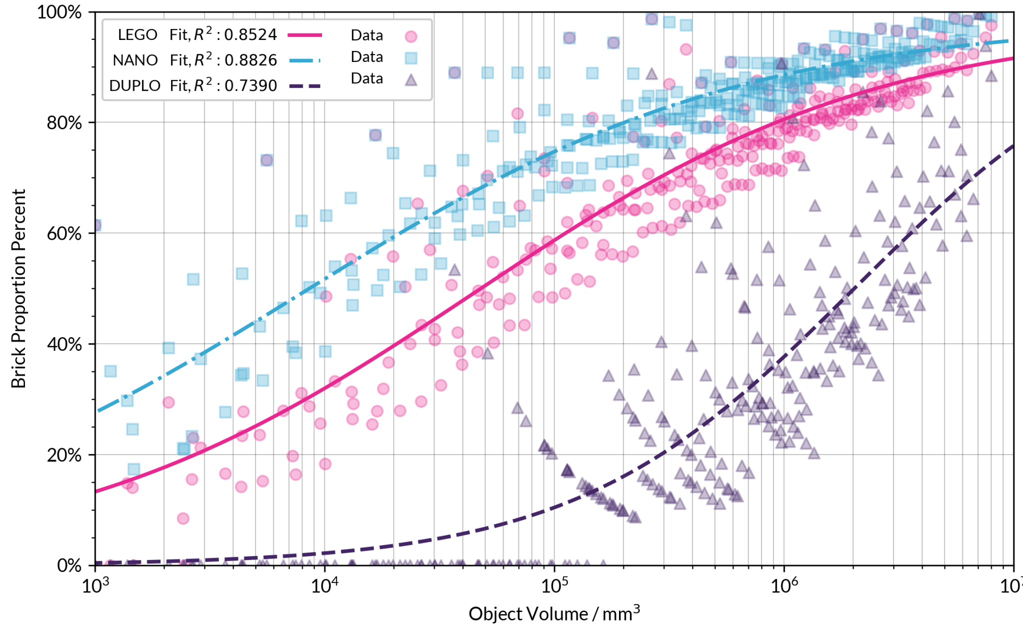


Figure 5.12 The Brick Proportion Percentage against Object Volume for the three brick sizes.

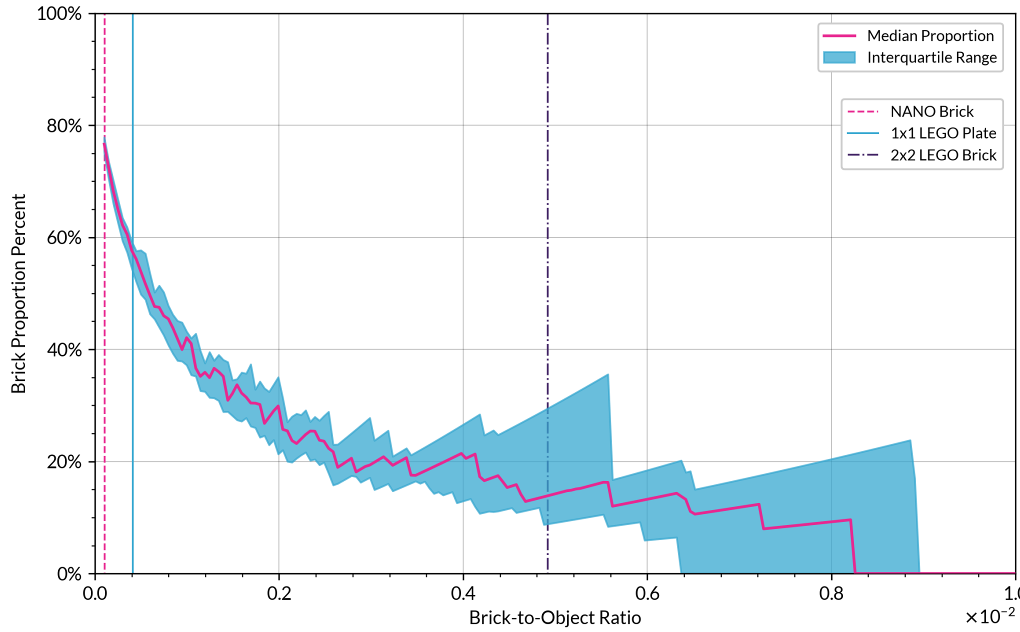


Figure 5.13 The brick proportion percentage against brick-to-object ratio. Reference ratios are also shown

Iterative Case Study

Figure 5.14 shows the results comparing using Hybrid Prototyping and solely 3D printing for each iteration of the games controller (see Figure 5.9). The print settings were kept constant as described in Section 5.3.1. It shows that there is a clear time saving in using Hybrid Prototyping over 3D printing each iteration.

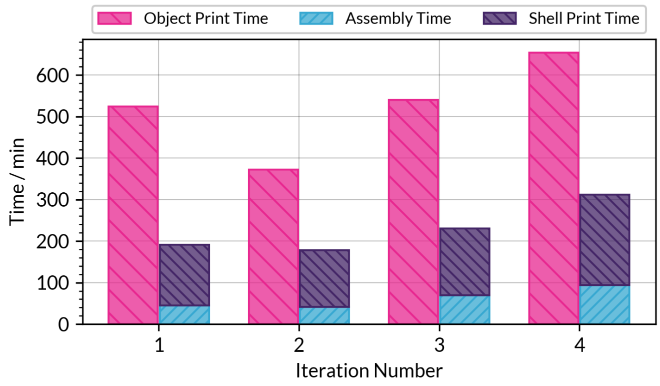


Figure 5.14 Fabrication times for each iteration against 3D printing the entire prototype iteration.

To better highlight how this time and material saving accumulates over successive iterations, a comparison of cumulative 3D filament material usage and time cost were plotted. These are shown in Figure 5.15.

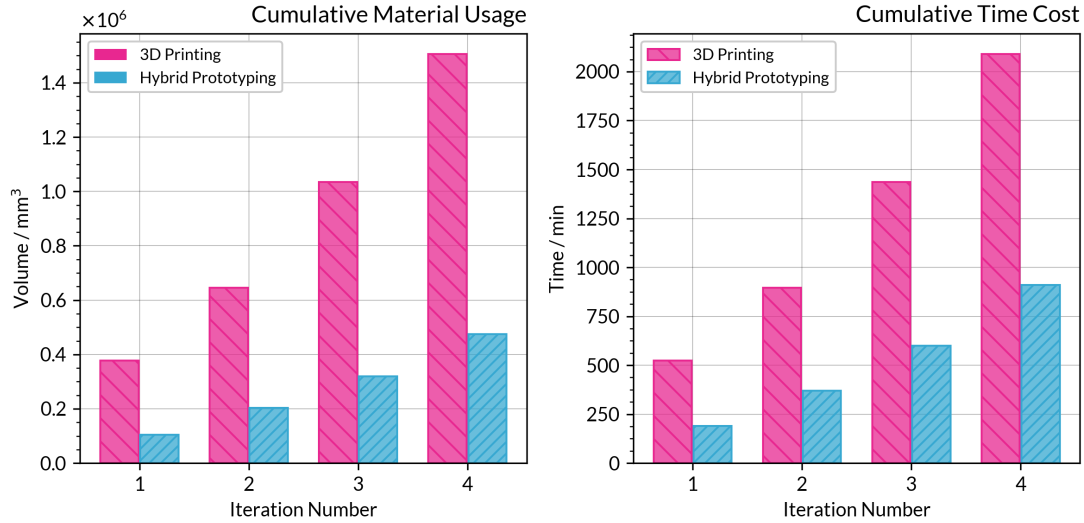


Figure 5.15 Two plots comparing the cumulative material usage (Left) and time cost (Right) over four iterations when using 3D Printing or Hybrid Method Prototyping.

5.4 Characterising the Benefits

As set out in the overview for this chapter, the aim was to establish and characterise the potential benefits of using a Hybrid Prototyping approach over simply 3D printing a prototype. From the simulation study and results, several characterisations of LEGO and 3D printed Hybrid Prototyping were found. Table 5.4 shows the potential benefits and optimum brick–to–object ratio found in the simulation study. This section outlines these benefits and how they characterise the use of Hybrid Prototyping.

Table 5.4 The potential benefits of Hybrid Prototyping in a single prototype instance

Fab. Time	Reusability	Brick:Object Ratio
−45 %	55 %	1:2500 - 1:1250

A key part of the benefits of HP is the dependence on the brick size – or more accurately the ratio between the brick size and the prototype size. Based on the median line in Figure 5.11, the optimum brick–to–object ratio lies between 1:2500 and 1:1250 for the objects investigated in this study. At this point, a 45 % reduction in fabrication time can be achieved. As a result, when using hybrid prototyping brick–to–object ratios of this order should be selected to minimise fabrication time. To contextualise this with a typical 3D print of *user–driven* products ($100 \times 100 \times 100$ mm dimensions, 1×10^6 mm^3 volume), the optimum ratio gives an optimum brick size of $10 \times 10 \times 4$ mm which is smaller than a DUPLO brick ($16 \times 16 \times 19.2$ mm) but only slightly larger than a LEGO brick ($8 \times 8 \times 3.2$ mm). Therefore, the first characterisation is that the relationship between prototype size and brick size have an impact on the fabrication time. Although custom brick sizes could be created for situation specific Hybrid Prototypes, for the remainder of this thesis only the commercially available construction kits, and in particular LEGO, will be considered.

From the results, it was found that the reusability of a Hybrid Prototype tends to 100 % as the brick–to–object ratio increases (i.e. smaller bricks). However, this conflicts with the target of minimising the fabrication time. Consequently, in order to maximise prototype reusability and minimise fabrication time, the brick-to-object ratios need to be selected at the ideal ratio. Using the ratio found from the fabrication time results the reusability is 55 %. This leads to the second characterisation; the smaller the bricks are in relation to the prototype, the more reusable the prototype becomes. But this needs to be balanced in the context of fabrication time.

The benefits of Hybrid Prototyping compound over multiple iterations. Table 5.5 shows the total material usage and fabrication time for the four iterations combined. Hybrid prototyping shows significant time and material savings of 56.4 % and 68.2 % respectively. This demonstrates that by using a hybrid approach to form–based prototyping the design process can be more efficient.

The simulation–based approach relied on several assumptions and so resulted in an

Table 5.5 Comparing the total material usage and time cost over four iterations for 3D printing and Hybrid Prototyping

	Fab. Time / min	Material / 10^6 mm^3
3D Printing	2090	1.51
Hybrid Prototyping	911	0.48
Difference / %	−56.4	−68.2

idealised version of Hybrid Prototyping. These assumptions were as follows:

- No decomposition of the hollow shell for generating the geometry to be printed.
- No consideration to the interface between the LEGO and printed parts.
- A simplified, analytical model of the printing process, resulting in approximate calculations of print times for a single printer.

Consequently, the results reported will be at the limit of what is possible when Hybrid Prototyping with LEGO and 3D printing.

However, despite the idealised nature of the study, the characterisations identified and potential benefits found still provide valuable insight into Hybrid Prototyping. The later chapters build upon and develop the approaches and algorithms reported in this chapter, refining Hybrid Prototyping with LEGO and 3D printing.

5.5 Concluding Remarks

The initial algorithms described at the start of this chapter provide the foundations for applying Hybrid Prototyping as a useful prototyping tool. The algorithms were then used in the simulation study reported in this chapter. The study provided answers to the first research question by demonstrating the theoretical benefits of Hybrid Prototyping through simulating the affect of different bricks sizes and geometries on the HP results. The potential time and material savings found were as follows (dependent on using the correct brick–to–object ratio):

- 45 % reduction in fabrication time
- 55 % reduction in material usage

However, due to the assumptions and limitations of the study, the results presented are an idealised version of Hybrid Prototyping, and further research is required to practically implement HP and maximise the benefits. These areas are addressed in Chapters 6 and 7 respectively.

Chapter 6

Physical Implementation

6.1 Overview

Chapter 5 showed the potential benefits of Hybrid Prototyping. These included a 45 % reduction in fabrication time, and 55 % reusability at this optimum fabrication time. However the impact of these findings cannot be realised unless the prototypes can be physically and practicably constructed. The second research question is:

> "RQ2: How can Hybrid Prototyping be implemented in practice?"

This chapter addresses the issues of practicality and answers the second research question through the development of the constraints, practical requirements, and software to implement the Hybrid Prototyping tool.

To achieve this, the research was split into five phases:

1. Review existing design rules for LEGO and 3D printing.
2. Establish design rules for Hybrid Prototyping.
3. Implementation of the design rules in the HP tool.
4. Evaluation of the impact of the design rules on fabrication time and reusability.
5. Identification of improvements and refinements.

To develop new design rules for hybrid prototyping with LEGO and 3D printing, the existing design rules and considerations for each prototyping method need to be reviewed (Phase 1). Correspondingly, Section 6.2 summarises relevant literature for the existing deign rules: design for additive manufacture (DfAM) and LEGO assembly.

Phase 2 builds on this review to develop and establish new design rules for Hybrid Prototyping. There is value in providing a more consistent framework and approach to maximise the benefits and usability of Hybrid Prototyping, as while existing approaches to Hybrid Prototyping (c.f. Section 3.3.1) have been shown to offer benefits, they are adhoc and lack structure on how to apply these novel approaches. The new design rules can ensure optimal time/cost/quality when producing prototypes. They also provides potential for computational offloading and automation, such as the techniques used by Mueller *et al.* [54] to automatically generate the LEGO brick layout. The new design rules are outlined in Section 6.3.

The research for Phases 1 & 2, reported in Sections 6.2 and 6.3, was published by the author at 22nd International Conference on Engineering Design (ICED 19), Delft, Netherlands [3].

Section 6.4 describes how the new design rules were integrated into the HP tool (Phase 3), including explanations of the algorithms developed.

Phases 4 and 5 are covered in Section 6.5 through employing the HP tool on three iterations of each of the three case study objects. The results are presented, with the key

[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*
[3] Mathias, D. et al. (2019) *Hybrid Prototyping: Pure Theory or a Practical Solution to Accelerating Prototyping Tasks?*

findings identified and tool improvements/refinements addressed. The chapter concludes by demonstrating how Research Question 2 has been answered.

6.2 Review of Existing Design Rules

The existing design rules that this section covers are a subset of Design for Manufacture and Assembly (DfMA). These consider how the design can be made, as well as identifying ways the manufacture and assembly can be simplified [144].

The following two sections describe the existing literature on DfAM and LEGO assembly, and the design rules that are currently employed.

6.2.1 Design for Additive Manufacture

Design for additive manufacture (DfAM) depends on the specific additive manufacture (AM) process employed – with each process having different rules and considerations. However, as the Hybrid Prototyping approach focusses on low cost FDM printing, the DfAM review will only consider those relevant to FDM printing. There are two areas in DfAM that the designer must understand: process considerations and geometric considerations [114].

The process considerations include the capability of the printers (size, accuracy, speed), material properties (strength, temperature, part anisotropy), and the print settings (layer height, infill percentage, wall thickness, support material etc). While the geometric considerations focus on the artefact being designed. Many of these variables are fixed by the use of desktop FDM printers – particularly with regard to material properties (typically limited to PLA or ABS) and capability of the printers. As previously stated in Section 4.5.2, a typical desktop FDM printer has an approximate build volume of $200 \times 200 \times 200$ mm, with X, Y, and Z resolutions of 12.5 µm, 12.5 µm and 20 µm respectively [137]. The print settings used impact the print time, part strength and quality but are not affected by the geometry of the part. For geometric considerations, there are guidelines on recommended values for particular geometric features in the design of FDM printed parts [101], as shown in Table 6.1. Following these guidelines mitigates many of the issues of anisotropic parts and the need for support material, improving quality and achieving parts that can be manufactured as designed.

Two aspects that bridge between process and geometry considerations are the print orientation and supported overhangs. While these aspects are dictated by how the printing process is setup, they need to be taken into account during the design process to ensure the printed parts meet requirements. Printed parts exhibit anisotropic behaviour under

[144] Boothroyd, G. et al. (2011) *Product Design for Manufacture and Assembly*
[114] Goguelin, S. et al. (2016) *A bottom-up design framework for CAD tools to support design for additive manufacturing*
[137] Ultimaker B.V. (2019) *Ultimaker 2+*
[101] Redwood, B. et al. (2017) *The 3D Printing Handbook*

Table 6.1 Guide values for geometric features on FDM printed parts (adapted from Redwood et al. [101])

Feature	Value	Limit
Wall Thickness	0.8 mm	Min
Overhangs	45°	Min
Engraved Details	0.6×2 mm	Min
Bridges	10 mm	Max
Holes	⌀2 mm	Min
Clearance	0.5 mm	Min
Feature size	2 mm	Min
Pins	⌀3 mm	Min
Unsupported Edges	3 mm	Max

loading due to their layered construction [145], as a result it is important, where possible, to ensure that parts are most heavily loaded parallel to the print layers to prevent delamination and failure. While support material can be added to create overhangs and bridges, it takes longer to print and often results in an undesirable surface finish, hence overhangs also need to be considered during the design process. Some geometric modifications can be applied to reduce the need for support material, such as adding chamfers under unsupported edges or ensuring circular profiles (in the vertical build direction) are changed to teardrop ones to prevent drooping at the top of the circle.

6.2.2 Design for LEGO Assembly

Although LEGO was originally designed as a children's toy, it has seen increased use as a tool for education and design – evidenced by the LEGO Group's creation of the Architecture Studio [95], allowing architects to quickly explore new building designs. As a result, there are established best practices that ensure that resulting models, whether a design output or toy kit, can be assembled and are strong enough to hold together.

Before describing different assembly techniques, there are fundamental aspects of LEGO that need to be considered when designing parts to be made from the construction kit. Firstly, LEGO bricks are discrete and can only be constructed at a fixed scale of 8 mm, in fixed, orthogonal planes. This means that objects can only have dimensions that are integer numbers of bricks and that complex curves can only be approximated with a 'pixelated' appearance. While there are more advanced techniques that mitigate this limitation, they are more challenging to implement and impact significantly on the reconfigurability of models and require substantial design and assembly effort [113]. Secondly, the size, and finite library, of LEGO bricks (the smallest being $8 \times 8 \times 3.2$ mm) means that there is a fixed lower bound of an object's size. On the other hand, while very large LEGO assemblies are possible, they are frequently too complex and costly to be

[145] Tymrak, B. M. et al. (2014) *Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions*
[95] The LEGO Group. (2013) *LEGO Architecture Studio*
[113] Enjary, D. (2007) *The Unofficial LEGO Advanced Building Techniques Guide*

viable outside LEGOLAND theme parks – giving rise to an upper bound for reasonably sized LEGO models.

Gower *et al.* [146] identified some general construction rules for creating stable LEGO structures:

- The use of large bricks;
- Alternating directionality of bricks in consecutive layers;
- High proportion of overlap of each brick's area (above and below) by other bricks;
- High proportion of each brick's vertical boundary is covered (above and below) by other bricks.

These rules do not include any design considerations that would affect the geometry or possible designs of the assembled model. They are purely focussed on creating assemblies that have structural integrity. Luo *et al.* [147] established a forced based approach to optimising LEGO assemblies, through experimentation they found that the separation force between two bricks was 0.703 N per stud. This is a conservative value, measured through worst case loading. By creating LEGO assemblies that do not exceed this value, there is sufficient structural integrity to support their own weight. Applying this to the joint between two 2×2 LEGO bricks, the join can support up to 0.286 kg (or 242 2×2 bricks) before failing in tension.

The Architecture Studio [95] offers higher-level assembly techniques that not only consider the strength of the design, but also how to overcome some of the limitations of LEGO – e.g. adding small details to the architectural designs. These techniques are shown in Table 6.2. Other than the *Locking* technique, all these guidelines are design considerations that the designer can use to build prototypes that are representative of their concepts.

Table 6.2 The LEGO assembly techniques as described in the LEGO Architecture Studio (adapted from The LEGO Group [95])

Technique	Description
Locking	Placing a brick over the joints to increase strength
Sideways building	Use bricks with studs on their sides to build sideways
Size Scaling	Build at small scale to show full scale objects
Details	Select textured/smaller bricks to show surface details
Alternative Uses	Use bricks in novel/different ways to create your designs
Building in Sections	Build smaller modules and bring them together later

[146] Gower, R et al. (1998) *Lego: Automated Model Construction*
[147] Luo, S.-J. et al. (2015) *Legolization: Optimizing LEGO Designs*
[95] The LEGO Group. (2013) *LEGO Architecture Studio*

6.3 Design Rules for Hybrid Prototyping

From the existing design rules for FDM printing and LEGO, it is possible to separate the rules into two groups: ones that are technical capabilities/limitations of the technique, and ones that the designer must consider when creating the design's geometry. In DfAM, these are called process and geometric considerations respectively [114]. However, in coupling LEGO and 3D printing as a hybrid prototyping technique, a finer level of granularity is required in order to accommodate the rules that influence the process plan and ones that require input from the designer. As a result, there are three groups of design rules to be considered:

- Technical Constraints
- Design Considerations
- Process Considerations

Figure 6.1 shows the relationship between the three groups of design rules, the design and planning (●), and the output hybrid prototype (●). The process and design considerations need the designer's input (●), while the technical considerations are fixed by the use and coupling of 3D printing and LEGO (●). The technical considerations and designer's process decisions are combined in the process planning that generates the LEGO assembly and decomposed 3D printed parts from the prototype geometry.

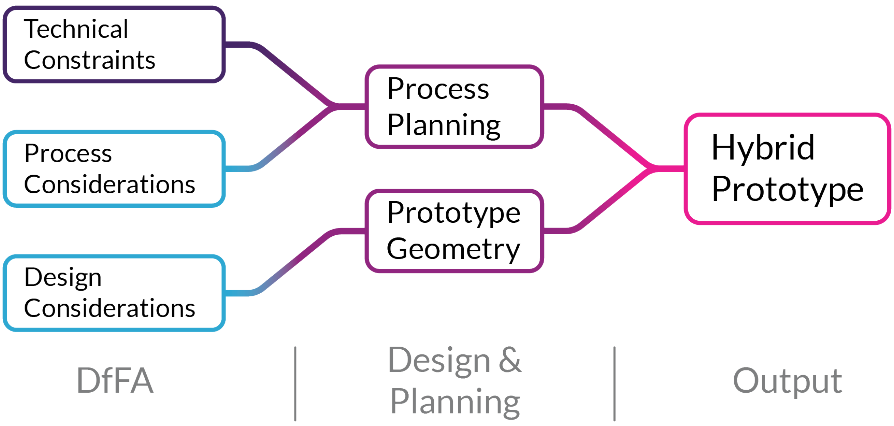


Figure 6.1 The relationship between the design rules and the hybrid prototype

The development of these design rules combined the literature review reported earlier in this chapter with practical exploration and iteration during the development of the algorithms. The use of an iterative design cycle during the algorithm and tool development was important to their creation. It brought to light issues and caveats that needed to be addressed by the design rules for Hybrid Prototyping – and so could be included in the list of rules.

The following sections cover the rules established for each of the three groups for hybrid prototyping. While reduction in fabrication time is cited as one of the key benefits

[114] Goguelin, S. et al. (2016) *A bottom-up design framework for CAD tools to support design for additive manufacturing*

of coupling LEGO and 3D printing [1], if the prototype cannot be made or is not self-supporting then this time reduction is irrelevant.

6.3.1 Technical Constraints

The technical constraints are fixed and cannot be impacted by the actions of the designer. These constraints inform the decisions and calculations that in turn drive the process planning that generates the LEGO assembly and 3D printed geometry.

1. *Assembly/Disassembly* – The prototypes must be able to be put together and taken apart. As a result, the LEGO pieces must be accessible via the split planes that separate the 3D printed outside surface.
2. *Structural integrity* – The hybrid prototype must be strong enough to be handled and support its own weight. This should be achieved by following the LEGO structure assembly rules described in Section 3.2. The process planning must layout the bricks to reduce the loading placed on any single stud to the acceptable bounds (0.703 N [147]).
3. *Composition of LEGO set* – The library of available brick sizes and their number needs to be specified in advance for the process planning to ensure that it does not generate prototypes that cannot be built due to insufficient available bricks.
4. *Number and size of the FDM printers* – The generated 3D printed parts must be small enough to be produced by the available printers. If more than one printer is available, there are opportunities to parallelise the printing and further reduce fabrication time as the printing time can be shared across multiple printers.

Assembly and structural integrity do not have fixed values that constrain the output (unlike the type/number of LEGO bricks available or size of the printers) but rather represent minimum bounds that need to be met during the process planning stage. As a result, there needs to be optimisation performed on the layout of the LEGO bricks and location of the decomposition slices of the 3D printed parts. These are discussed in later chapters.

6.3.2 Design Considerations & Checks

The design checks are aspects that the designer must take into account when specifying the form, shape and geometry of the prototype. If the design fails these checks then it is not suitable for LEGO and 3D printing hybrid prototyping.

5. *Overall size* – The design must fit between certain overall dimensional bounds that ensure that hybrid prototyping is a suitable method to embody the prototype. If it is too small ($<10 \times 10 \times 10$ mm) then the design cannot accommodate any LEGO and will be entirely 3D printed. Conversely, if the design is too big

[1] Mathias, D. et al. (2019) *Accelerating product prototyping through hybrid methods: Coupling 3D printing and LEGO*
[147] Luo, S.-J. et al. (2015) *Legolization: Optimizing LEGO Designs*

(>500 × 500 × 500 mm), then the high number of bricks required and resulting slow fabrication time makes other prototyping techniques more suitable.

6. *Minimum dimension/thickness* - Similar to the overall size, the design cannot have a dimension or thickness smaller than a LEGO brick (i.e. a thin plate or thin-walled box). The smallest LEGO brick is 8 × 8 × 4 mm (including the stud) and so allowing for connection between the brick and 3D printed part, the dimensions of the prototype must be larger than 10 mm. However slender regions can exist so long as other parts of the design are large enough to be constructed out of LEGO.
7. *Feature size* – As the outside surface of the prototype is 3D printed, any features must conform with the DfAM recommended values described in Table 6.1. Overhang angle and unsupported edge length can be excluded as the 3D printed parts will be re-orientated for printing.

6.3.3 Process considerations

The process considerations are designer decisions that do not affect the design geometry and dictate what variables the process planning should use to create the hybrid prototype. These are akin to the print settings in slicing software for FDM 3D printing.

8. *Size/number of decomposed 3D printed parts* – Choosing between fewer, larger parts (with fewer splits) or a greater number of smaller parts allows the designer to control the level of modularity and flexibility the prototype has. Furthermore, if more than one printer is available then a greater number of parts will mean that the overall fabrication time can be reduced.
9. *Location of split planes* – As the outer surface shell has to be decomposed, the split planes may intersect a critical feature. This would allow the designer to choose which particular feature or geometry gets preserved. For example, ensuring that a button on an interface remains complete. However, this would not override the technical consideration of the requirement to be able to assemble/dissemble the prototype.
10. *Level of fidelity* – Extending the theoretical findings of Mathias *et al.* [1] it can be contended that the fabrication time can be further reduced by only printing the areas of required high fidelity. This consideration would allow designers to select the regions of interest in their design requiring higher fidelity leaving the remaining regions to be approximated by LEGO.
11. *LEGO usage* – Another way to reduce fabrication time and LEGO brick usage, is to generate a hollow LEGO assembly. However, this would impact the strength and weight of the prototype. The designer must consider what they want to achieve with the prototype.
12. *FDM 3D printer settings* – Print settings have a large impact on the output from the printer, particularly with regard to a part's strength [148]. However, in hybrid

[1] Mathias, D. et al. (2019) *Accelerating product prototyping through hybrid methods: Coupling 3D printing and LEGO*

[148] Goudswaard, M. et al. (2018) *Towards the Democratisation of Design: Exploration of Variability in the*

prototyping the strength of the prototypes is limited by the inter-part connection therefore the standard printed, regardless of orientation can be considered to be sufficiently strong. The settings for print speed (which will affect the fabrication time) are printer and filament dependent and need to be determined for specific printers.

6.4 Implementation of Design Rules

The initial algorithms for the Hybrid Prototyping tool are described in Chapter 5:

- *Brixellation* – calculates the positions of LEGO bricks inside the geometry.
- *Packing* – generates the LEGO structure and list of required bricks.
- *Shelling* – generates the outer geometry that is to be 3D printed.

The implementation of the DfFA rules builds on these three algorithms, integrating the required checks and additional functionality into the Hybrid Prototyping tool.

This section describes the development of the HP tool, outlining how the design rules were incorporated. It is broken into three subsections that address the 12 rules established in Section 6.3:

- *Designer Input* – the aspects of the HP tool that need to be determined by the designer.
- *Geometry Checks* – simple pass/fail checks that decide if the geometry is suitable for prototyping with the HP tool.
- *Assembly & Print Algorithms* – the algorithms that decompose the hollow shell and ensure the assemblability of the prototype.

6.4.1 Designer Input

Several of the rules established require the Hybrid Prototyping tool to have input from the designer.

Rule 3 requires the designer to define the composition of the LEGO set. This is done in the custom Blender GUI. Figure 6.2 shows the GUI with different bricks selected to be used in the *Packing* algorithm.

Rule 8 considers the size and number of 3D printed parts, asking the designer to make a choice between fewer, larger parts and more, smaller parts. This is primitively implemented in the tool development described in Section 6.4.3: the designer can control the number of vertical cuts used to split the geometry. This is presented to the designer as a numerical input slider in the GUI, letting the designer choose between 0 and 20 cuts.

Rules 9 to 11 do require designer input but are not considered in this chapter. These are more advanced process considerations that are investigated in Chapter 7.

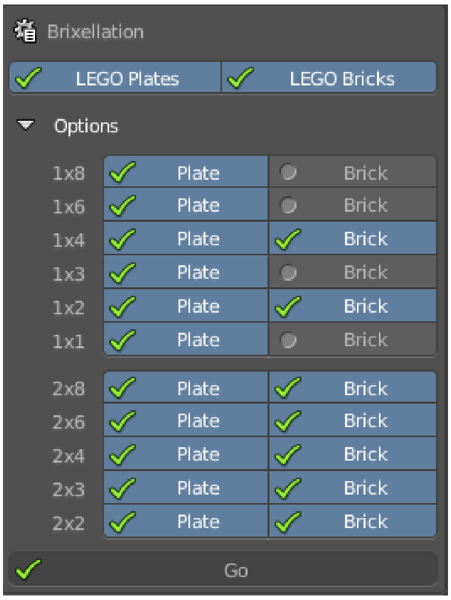


Figure 6.2 A section of the Hybrid Prototyping tool GUI that shows different bricks selected

The print settings (Rule 12) have an impact on the fabrication time, material usage, material properties of the parts. The number of variables to consider and differences between real-world printers means that creating general optimisations is difficult. As a result is considered out of scope for this thesis.

6.4.2 Geometry Checks

The geometry checks analyse the input prototype geometry to ensure that the prototype can be fabricated using Hybrid Prototyping. These checks are performed before *Brixellating* the geometry: giving a pass/fail result that informs the designer if the geometry is unsuitable.

Rule 5 considers the overall size of the geometry. The bounding box dimensions of the input geometry are checked to ensure that HP is suitable. The upper and lower bounds are: $500 \times 500 \times 500$ mm and $10 \times 10 \times 10$ mm.

Rule 6 checks the minimum dimension of the geometry is larger than a LEGO brick. This checks thin regions using Blender's in-built geometry analysis tools. The geometry is suitable if there is at least one region that is thick enough to accommodate LEGO bricks.

Rule 7 ensures that the geometry conforms with the DfAM rules outlined in Table 6.1. The HP tool leverages Blender's in-built 3D print analysis tools to check for very small, slender or sharp geometric features.

If the geometry passes all the checks then the tool can proceed with the necessary algorithms.

6.4.3 Assembly & Print Algorithms

The assembly and print algorithms form the majority of the Hybrid Prototyping tool development that builds on the initial algorithms.

Shell Decomposition

The resulting printed geometry from the Shelling algorithm is hollow, with the LEGO occupying its internal volume. As it stands this hollow single part cannot be assembled into a Hybrid Prototype. Therefore, Rule 1 of DfFA is that the shell must be split as to ensure that the prototype can be assembled. This similar to the approach Vanek *et al.* [149] employed to convert objects into shells and break them into smaller parts for the benefits of saving support material and print time. It also allows multiple parts to be packed within the print volume [150] or a large parts to be spread across multiple print volumes [151], [120].

The shell decomposition consists of separating this hollow shell with planar cuts to ensure the Hybrid Prototype can be assembled and is modular. Oh *et al.* [152] identified three boundary cut shapes that are used to decompose objects: planar, voxel, and free-form. Song *et al.* [153] created a method for generating inter-locking parts but it is not suitable for hollow shapes and so was not considered for this application. For the purposes of demonstrating the HP tool, planar cuts are used and are kept perpendicular (X-Z or Y-Z planes) or parallel (X-Y plane) to the ground plane – other cut shapes, orientations, and directions could be considered as optimisations but are out of scope.

LEGO can only be assembled in a single orthogonal direction, which for the purposes of the development of this HP tool, is aligned with the vertical axis of the object. Correspondingly, the critical cuts must be horizontal (i.e. parallel to the ground plane) to guarantee that the LEGO can be assembled inside the prototype. Figure 6.3 illustrates the shell decomposition in a 2D diagram.

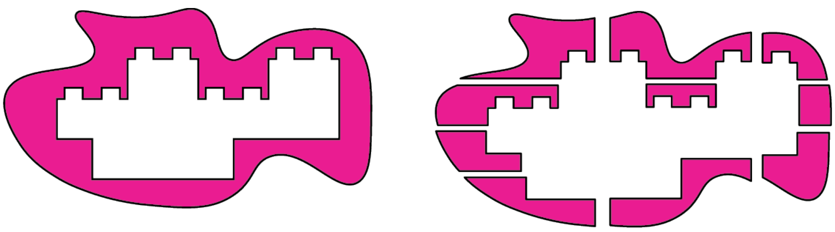


Figure 6.3 A 2D diagram illustrating the decomposition of the hollow shell

The position and number of the horizontal cuts is determined by the arrangement of the

[149] Vanek, J. et al. (2014) *PackMerger: A 3D print volume optimizer*
[150] Yao, M. et al. (2015) *Level-set-based partitioning and packing optimization of a printable model*
[151] Oh, Y. et al. (2017) *Part Separation Methods for Assembly Based Design in Additive Manufacturing*
[120] Song, P. et al. (2016) *CofiFab: Coarse-to-Fine Fabrication of Large 3D Objects*
[152] Oh, Y. et al. (2018) *Part decomposition and assembly-based (Re) design for additive manufacturing: A review*
[153] Song, P. et al. (2015) *Printing 3D objects with interlocking parts*

LEGO bricks. The underlying rule that governs the location of the cuts is whether a brick interfaces with a 3D printed part. In which case, the cut should fall within the height of that brick. This is described in Equation 6.1. The packed brick array, B^P of size $I \times J \times K$ (as defined in Equation 5.2), contains the indices of each of the N bricks.

$$C_H \ni \begin{cases} k & \text{if } B^P_{i\,j\,k\pm 1} = 0 \\ \varnothing & \text{otherwise} \end{cases} \qquad \text{where } B^P_{i\,j\,k} = n \qquad (n \in N) \tag{6.1}$$

where C_H is the set of height indices where cuts should be placed to ensure the prototype can be assembled.

The real world vectors, $\vec{P_h}$, that define the mid point of each plane for horizontal cut are calculated using Equation 6.2.

$$\vec{P_h} = \begin{bmatrix} 0 \\ 0 \\ c_H \end{bmatrix} \begin{bmatrix} w & d & h \end{bmatrix} + \vec{s} \qquad (c_H \in C_H) \tag{6.2}$$

where C_H is calculated in Equation 6.1, $\vec{s}$ is the start point of the geometry (defined in Equation 5.3), and $[w\, d\, h]$ are the dimensions of the 1×1 LEGO plate.

In order to increase the modularity of the prototype (Rule 8), the geometry can be split using vertical cuts. If the geometry is cut vertically before the horizontal cuts are generated, then the packed brick array, B^P, has to be sliced to match the geometry of each of the resulting parts. This subset, b^P is then used in Equation 6.1, with N_b being the set of distinct brick numbers within b^P (see Equation 6.3).

$$N_b = \{\text{distinct } n \in b^P\} \qquad \text{where } b^P \subseteq B^P \tag{6.3}$$

The locations of the vertical cuts is arbitrary, and in the case studies described in Section 6.5, they are defined by the number of the cuts set by the designer. The cuts are evenly distributed along the greatest dimension of the object, with no consideration to the underlying geometry or print times. This limitation is addressed in Chapter 7 in how the HP tool can be improved.

Print Checks

The final check is that the resulting printed parts will fit on the bed of a FDM 3D printer (Rule 4). The dimensions of each part are checked to be within $200 \times 200 \times 200$ mm (standard bed size, though this can be changed by the designer). If a part is larger than those dimensions, the designer is asked to rerun the shell decomposition with more vertical cuts to ensure that all the resultant parts can be printed.

6.5 Case Studies

To demonstrate and investigate the implementation of Hybrid Prototyping, the development of the tool was tested against the case study objects introduced in Chapter 4. The aim of these case studies is to characterise the implementation of HP with respect to the fabrication time and reusability. This section describes the experimental simulations used, and presents the results before discussing the findings.

6.5.1 Method

The overall approach used was to simulate the implementation of the Hybrid Prototyping tool to evaluate the impact of the DfFA rules. The key metrics investigated were the fabrication time and reusability (as first introduced in Chapter 5). The calculation of these metrics is described later in this section.

As the simulation approach is deterministic, it only needs to be run once for each combination of independent variables, as repeated runs do not result in different values. The variables used are described later in this section.

Calculation of Metrics

The reusability was calculated using the same volume based approach defined in Equation 5.14. Similarly, the fabrication time was calculated using Equation 5.13. However, there were two adjustments made to the estimated print rate and to the assembly time.

For the assembly time, the brick count and the printed part count were included to generate a more realistic time taken to assembly the prototype. This made the assumption that the printed parts could be assembled at the same rate as the LEGO bricks.

The print rate estimate evolved to match the increased sophistication of the Hybrid Prototyping tool. The model is based on both the volume and surface area of the part to be printed. This allows the estimation to more closely represent how an FDM printer prints a part, with different speeds for the sparse infill versus the perimeter walls. These print rates are shown in Figure 6.4: a wall speed of 109.86 mm^3/min, and an infill speed of 166.63 mm^3/min. It is worth noting that speed is per unit volume of the original geometry not the volume of material deposition in the printed part.

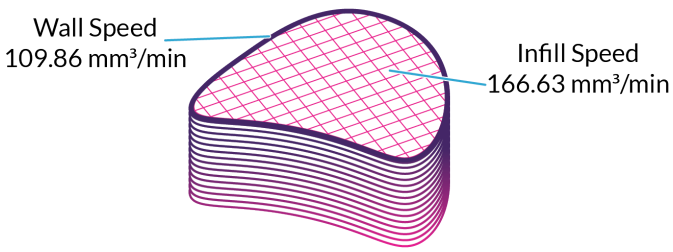


Figure 6.4 The print speeds of the sparse infill versus the perimeter walls

The updated model, therefore requires the volumes apportioned to the perimeter wall, V_w, and sparse infill, V_i. Equation 6.4 shows how these two volumes are calculated.

$$V_w = S_o \cdot t \qquad V_i = V_o - V_w \tag{6.4}$$

where S_o is the object's surface area, t is the wall thickness (an FDM printer setting, kept at 0.7 mm for this study), and V_o is the volume of the object.

Equation 6.5 calculates the resulting print estimate, P_e, from these two equations.

$$P_e = V_w \cdot R_w + V_i \cdot R_i \tag{6.5}$$

where R_w and R_i are the print rate per volume for the wall and infill respectively. These values were calculated empirically using Cura slicing software [131].

This equation provided a more accurate estimate (than the model used in Chapter 5) - particularly for calculating the print times of the more complex parts that included surface detail and the LEGO interface.

Variables

The three independent variables used in the experiments were the objects, the number of vertical slices, and the types of bricks used. These variables are shown in Table 6.3 and are discussed in more detail in the following section.

Table 6.3 The independent variables used in the case studies

Variable	Description	Values
Objects	The target geometry of the prototype	3×computer mouse, video game controller, and digital camera
Vertical Cuts	Number of vertical cuts to split the geometry	0-5 cuts
Types of Brick	The smallest brick size used in the packing	bricks or plates

Objects

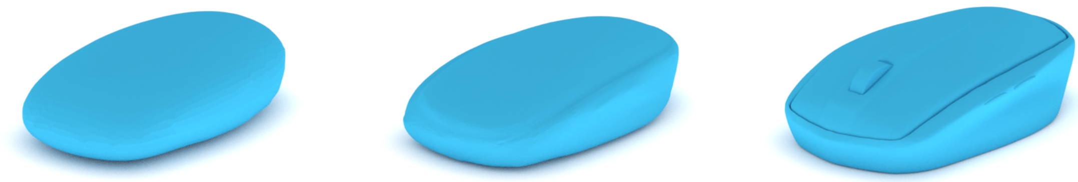
In order to demonstrate the HP tool across iterations, the three case study objects were artificially simplified to create three separate iterations. Each iterations has increasing complexity and detail, this ensures that affect of required surface detail and fidelity to be considered in the case studies.

Figures 6.5 to 6.7 show the three iterations for each of the case study objects.

Vertical Cuts

As discussed in Section 6.4.3, the 3D printed shell has to be decomposed in order for the prototype to be assembled. For bottom-up vertical assembly (ensuring compatibility with LEGO), the horizontal cuts are dictated by the underlying LEGO structure and so are dependent variables. However, the number and position of the vertical cut can be

[131] Ultimaker B.V. (2018) *Ultimaker Cura 3.6.0*

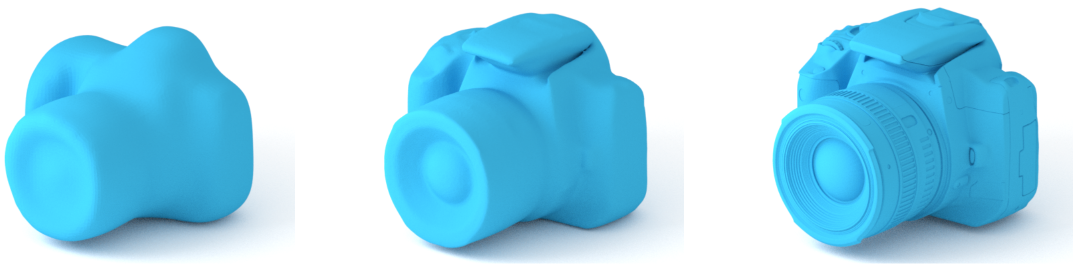


(a) Iteration 1 (b) Iteration 2 (c) Iteration 3

Figure 6.5 The three iterations of the computer mouse

(a) Iteration 1 (b) Iteration 2 (c) Iteration 3

Figure 6.6 The three iterations of the video game controller



(a) Iteration 1 (b) Iteration 2 (c) Iteration 3

Figure 6.7 The three iterations of the digital camera

controlled. For this experiment, the vertical cuts are distributed evenly along the largest dimension of the object.

The number of vertical cuts varies from none (only horizontal cuts) through to five. The vertical cuts are only added in one dimension.

Brick Types

The brick types investigated in these case studies consider the smallest LEGO piece used. This determines the level of reusability of the prototype and the bricks used in the packing. The two variables considered are:

- *Plates* – smallest piece is 1×1 plate (8 × 8 × 3.2 mm), and includes all the brick sizes described in Table A.2.
- *Bricks* – smallest piece is 1×1 brick (8 × 8 × 9.6 mm), and includes the brick sizes in described in the right side of Table A.2.

6.5.2 Results

The results from the simulations are presented in this section. These are split into three main sections:

- Overall fabrication times
- Reusability and part count
- Distribution of part print times

Fabrication Times

The overall fabrication times is the combined time taken for the required parts to be printed and assembled together with the LEGO bricks.

Figure 6.8 shows the distribution of the fabrication times when combining the data from the number of cuts and types of brick used. Each plot shows the fabrication times for the iterations of the object.

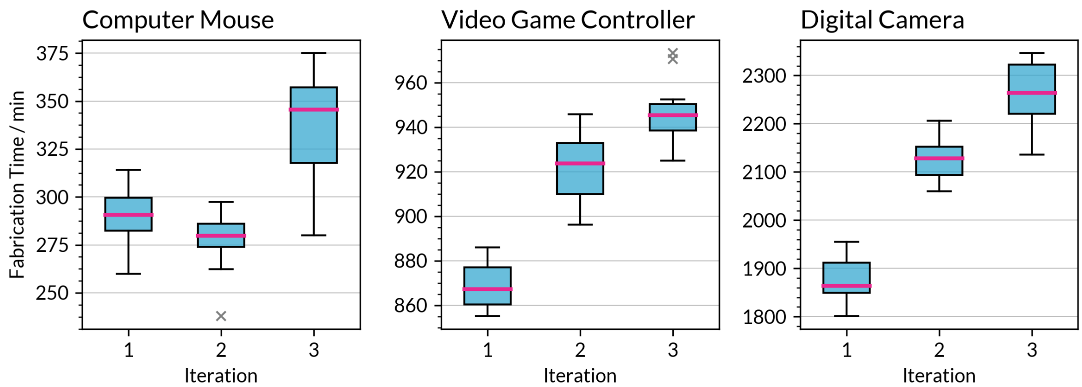


Figure 6.8 The distribution of fabrication times for the three iterations of the three objects

The first observation is that as the level of surface detail increases across the iterations, so does the average fabrication time. The second is that it is apparent that the brick type and the number of vertical cuts can result in a wide range of fabrication times.

The underlying data for Figure 6.8 can be found in Figures 6.9 to 6.11, showing the fabrication times for the three iterations of the three objects. These plot the number of vertical cuts against the fabrication times for when using plates or bricks.

On the whole, the fabrication time increases with the number of vertical cuts. The increase can be mostly attributed to the print times rather than the assembly time - the small assembly time increase from more parts (see Section 6.5.2) is outweighed by the increase in print time. The increase in total print time is due to the increased surface area per unit volume arising from splitting the same object into more parts (see Equation 6.5).

Table 6.4 shows the percentage differences in fabrication times between using LEGO plates over bricks. The table shows that as the object's size increases the difference in

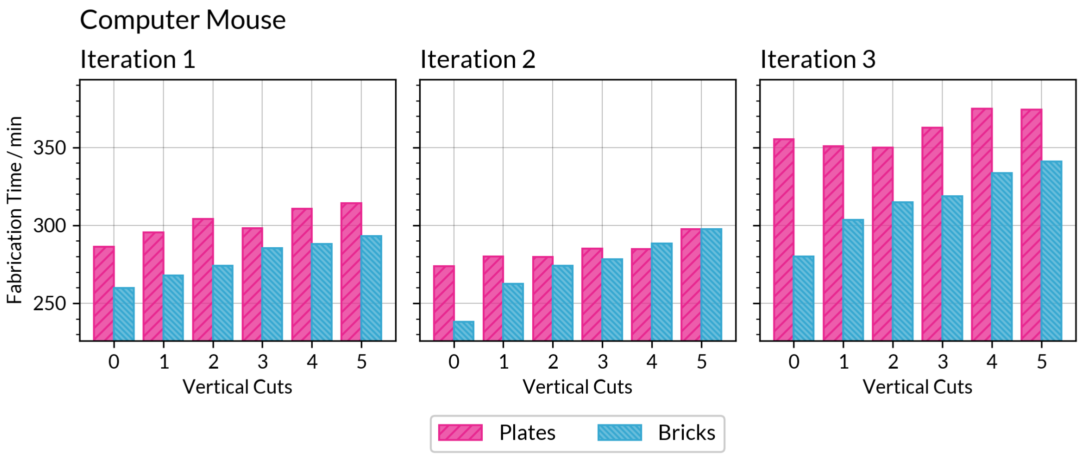


Figure 6.9 The fabrication times for the three iterations of the computer mouse

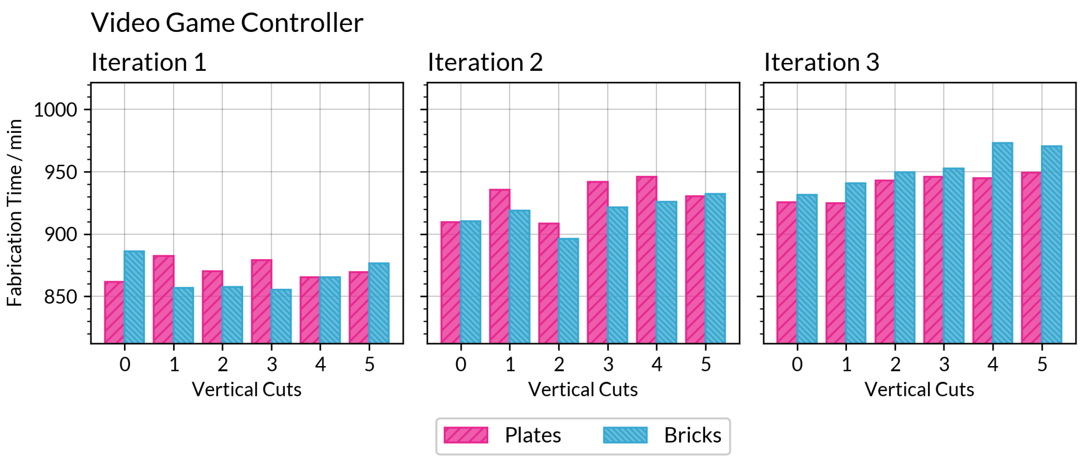


Figure 6.10 The fabrication times for the three iterations of the video game controller

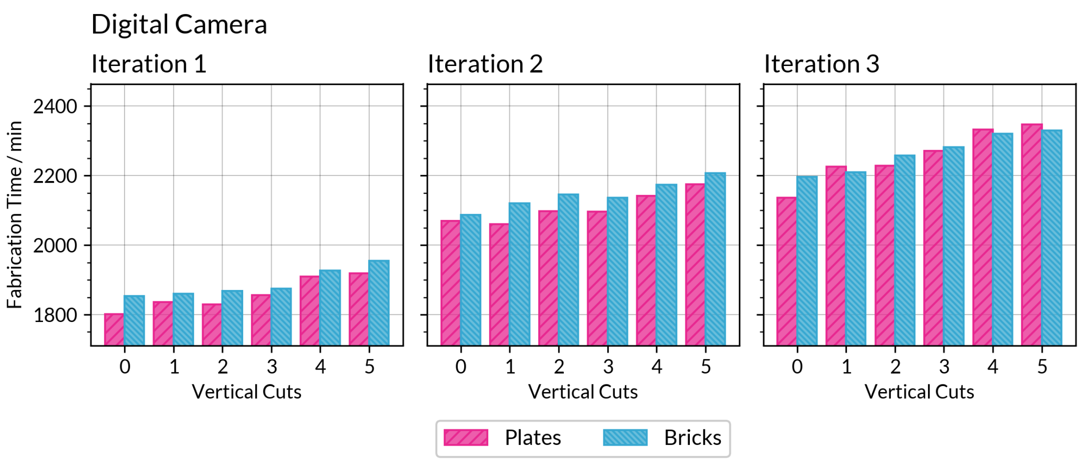


Figure 6.11 The fabrication times for the three iterations of the digital camera

fabrication time between brick types reduces, and then inverts – meaning that in large objects there is no benefit in using the smaller brick types.

Table 6.4 Fabrication time difference between using LEGO plates over bricks

Object	Iter. 1 / %	Iter. 2 / %	Iter. 3 / %	Average / %
Computer Mouse	8.41	3.81	14.59	8.94
Video Game Controller	0.59	1.20	−1.49	0.10
Digital Camera	−1.63	−1.77	−0.42	−1.28

Figure 6.12 compares the average print and assembly times against printing the object as a single piece. The average is taken from the fabrication and assembly times for each of the number of cuts and brick types (12 data points) The average was calculated for each of the iterations.

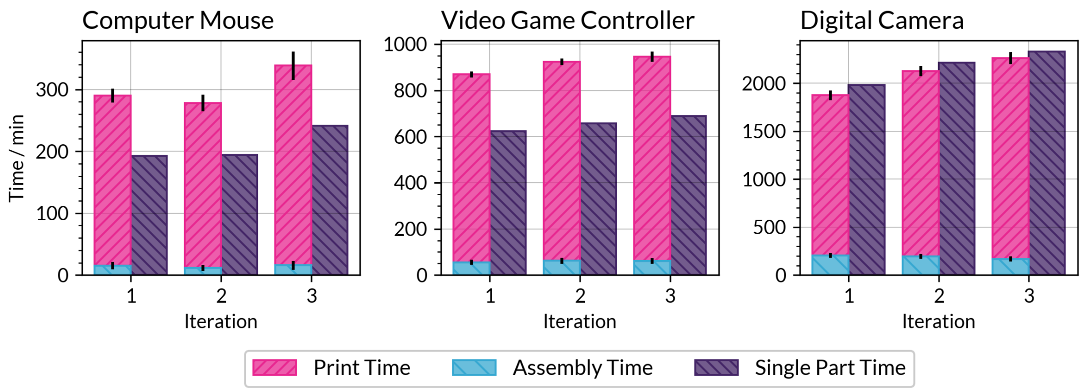


Figure 6.12 The breakdown of average fabrication times compared to the time taken to print the object

Table 6.5 shows the percentage differences between using the Hybrid Prototyping tool and printing the prototype as a single part. When using a single printer, it only becomes quicker to use HP with the largest object (the digital camera).

Table 6.5 Average fabrication time difference between Hybrid Prototyping and printing as a single part

Object	Iter. 1 / %	Iter. 2 / %	Iter. 3 / %	Average / %
Computer Mouse	50.63	43.55	40.44	44.87
Video Game Controller	39.44	40.48	37.39	39.11
Digital Camera	−5.31	−4.07	−2.90	−4.09

Reusability

Figures 6.13 to 6.15 show the LEGO and printed part counts for the three iterations of the case study objects across the different vertical cuts. As expected the LEGO part counts remain constant as the number of cuts increase, while the number of printed parts increase. In all cases, the overall part count is dominated by the number of LEGO bricks.

Figure 6.16 shows the reusability, the proportion of the geometry that can be made from LEGO, for the three iterations of the case study objects. This does not consider the reuse

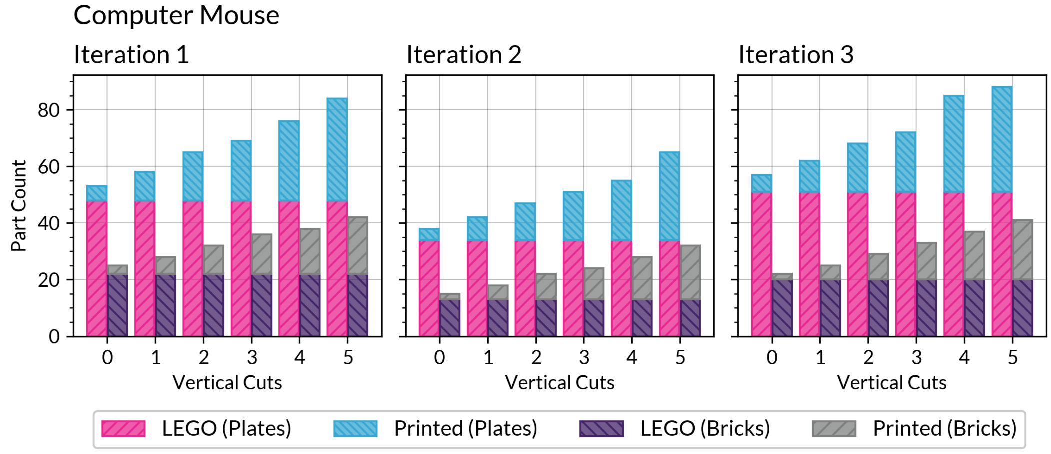


Figure 6.13 The part counts for the three iterations of the computer mouse, comparing using LEGO plates or bricks as the smallest brick

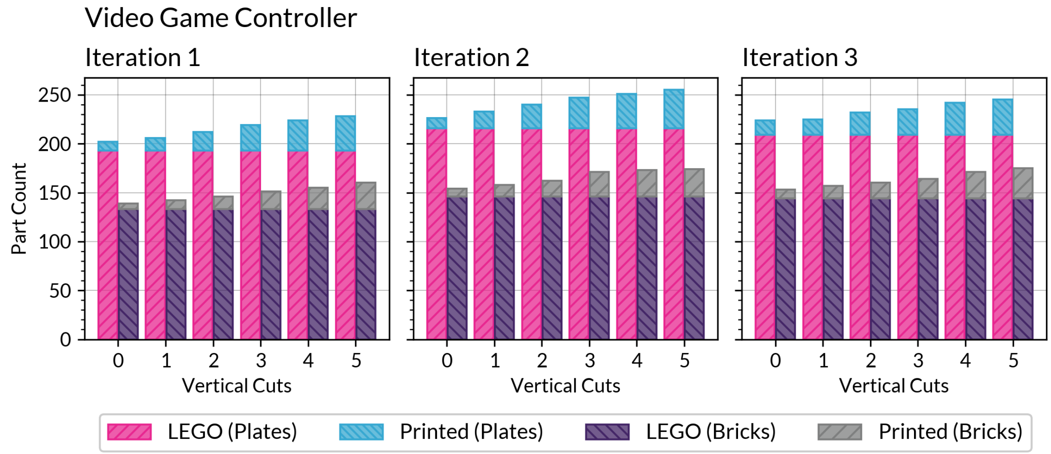


Figure 6.14 The part counts for the three iterations of the video game controller, comparing using LEGO plates or bricks as the smallest brick

of the printed parts between iterations.

Table 6.6 shows the percentage difference in reusability between using LEGO plates over bricks. This shows that the difference in reusability between brick types reduces as the object's size increases.

Table 6.6 Reusability difference between using LEGO plates over bricks

Object	Iter. 1 / %	Iter. 2 / %	Iter. 3 / %	Average / %
Computer Mouse	25.76	24.32	25.01	25.03
Video Game Controller	14.38	15.92	15.15	15.15
Digital Camera	4.68	5.00	5.77	5.15

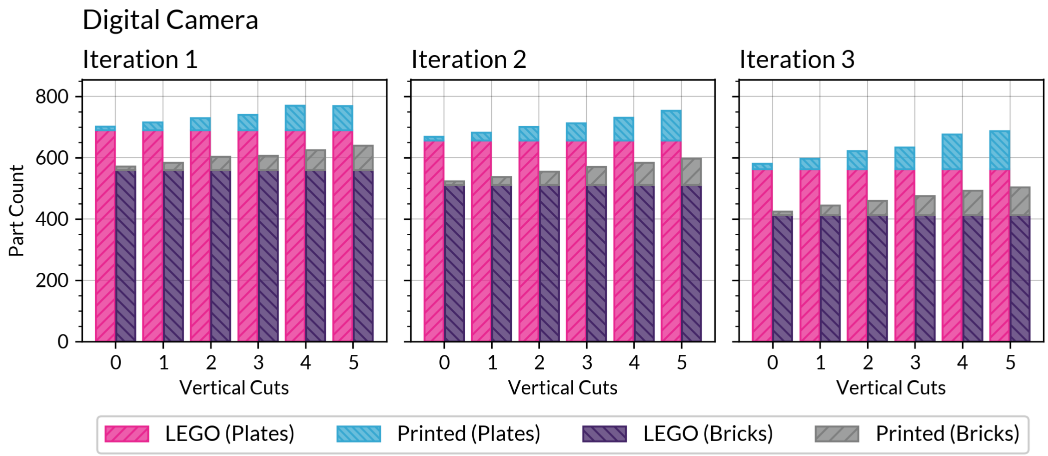


Figure 6.15 The part counts for the three iterations of the digital camera, comparing using LEGO plates or bricks as the smallest brick

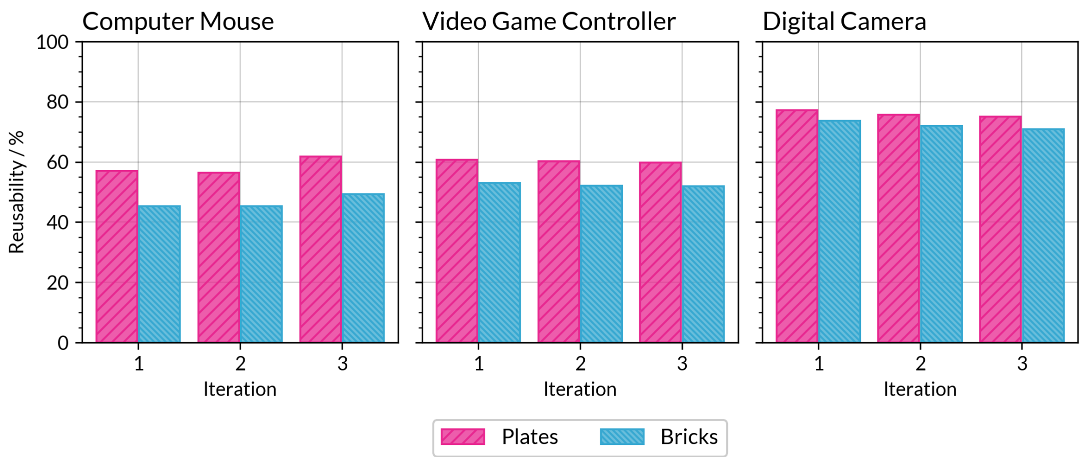


Figure 6.16 The reusability of the prototypes for the three iterations of the case study objects

Part Print Distributions

The part print distributions are the spread of print times for each of the decomposed shell pieces. This is provides insight into how the Hybrid Prototype has been decomposed and the opportunities for balancing the printing load across multiple printers (see Section 7.2.3).

Figures 6.17 to 6.19 show the distributions of the individual times for the printed parts. Boxplots are plotted for each of the iterations with the number of vertical cuts and brick type shown.

These plots show that as the number of vertical slices increases, the range and spread of individual print times reduces It also shows that the average part print time gets smaller as the number of parts increases.

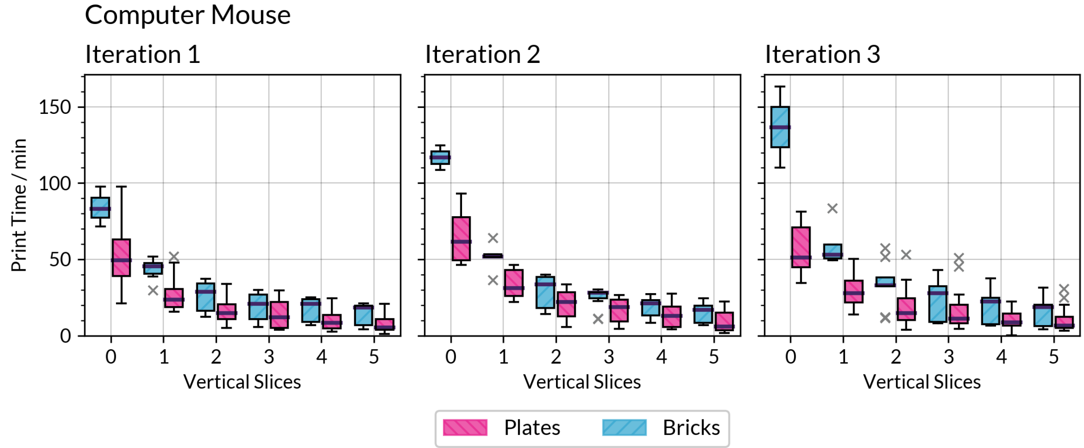


Figure 6.17 The distribution of the print times of the individual parts for the three iterations of the computer mouse, comparing using LEGO plates or bricks

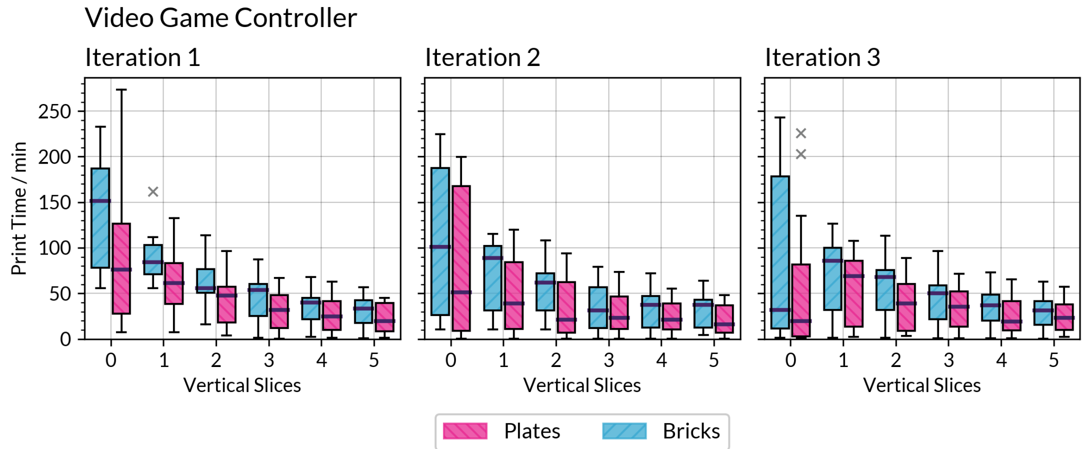


Figure 6.18 The distribution of the print times of the individual parts for the three iterations of the video game controller, comparing using LEGO plates or bricks

6.5.3 Key Findings

The case studies reported in this chapter show that the implementation of the Hybrid Prototyping tool was achieved and its impact on the fabrication time and reusability.

The first key finding is that it is possible to create assemblable hybrid prototypes that are practical to fabricate. However when only using one printer (or serially printing the parts), the caveat to this is the fabrication times do not align with the potential benefits quantified in Chapter 5. This discrepancy arises from the simplistic print model, used in Chapter 5, that was then improved to take into account the increased surface area of decomposing the geometry. In fact, with the exception of the digital camera, all the iterations of the computer mouse and video game controller took significantly longer to fabricate that purely printing them. Consequentially, the effect of multiple printers and parallelising the printing needs to be investigated to see if the potential benefits results could be matched. This is an extension of Rule 4 – the need to consider the number and

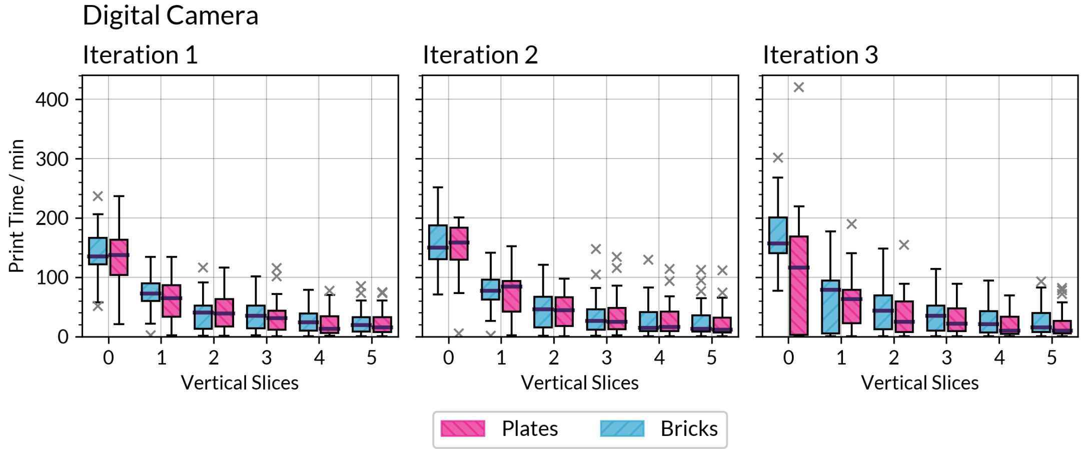


Figure 6.19 The distribution of the print times of the individual parts for the three iterations of the digital camera, comparing using LEGO plates or bricks

sizes of the available printers.

The second key finding is that there is very little difference in fabrication time between using LEGO plates as the smallest part against using LEGO bricks. This is particularly apparent in the digital camera where in fact it is quicker produce a prototype when only using LEGO bricks. This means that if just using LEGO bricks, then the number of assembly parts can be reduced – reducing the time spent assembling the prototype. However, the brick type used does have an impact on the level of reusability of the prototype. When using LEGO plates, the level of reusability is higher that using bricks. This phenomenon reduces as the prototype object gets larger. So in the case of choosing the brick types permitted (see Figure 6.2) the designer must make a decision about the required fabrication speed versus prototype reusability and material use.

The third finding is that the distribution of part times decreases as the number of printed parts increases. This shows that more parts an object is decomposed into the easier it is to split across multiple printers. It also shows that there is a need to balance the print times of the generated parts, especially when the object is decomposed into fewer parts. Balancing would mean that all the parts can be printed in approximately the same length of time across multiple printers.

6.5.4 Tool Refinements

Through the realisation of the Hybrid Prototyping tool employed in the case studies, it became apparent that some further refinements were required to improve the tool's usability and performance. The two refinements were:

- Modifying the LEGO-printed part interface to improve the assembly.
- Creating assembly instructions to reduce assembly time.

These are described in the following sections.

Printable Interface

Due to LEGO's high precision injection moulding, the bricks have a tight tolerance that allows them to snap together. FDM printers can not match this tolerance – particularly when creating circular and round features. Despite over-sizing the female holes on the printed parts, the variability of the printer resulted in poor interfacing between the male LEGO studs and the female printed part. It meant that assembling the prototypes was difficult or required considerable force. As a result, the interface between the LEGO bricks and printed parts needed to be redesigned to ensure that the parts would fit, be easier to assemble, and hold securely together.

Figure 6.20 shows the redesigned female geometry. The design changes took inspiration from interference fit used on standard LEGO bricks. It reduced the points of contact with the LEGO stud to four, making the interface more suitable for lower tolerance printing. The updated interface was incorporated into the *shelling* algorithm to improve the interface when generating the geometry to print.

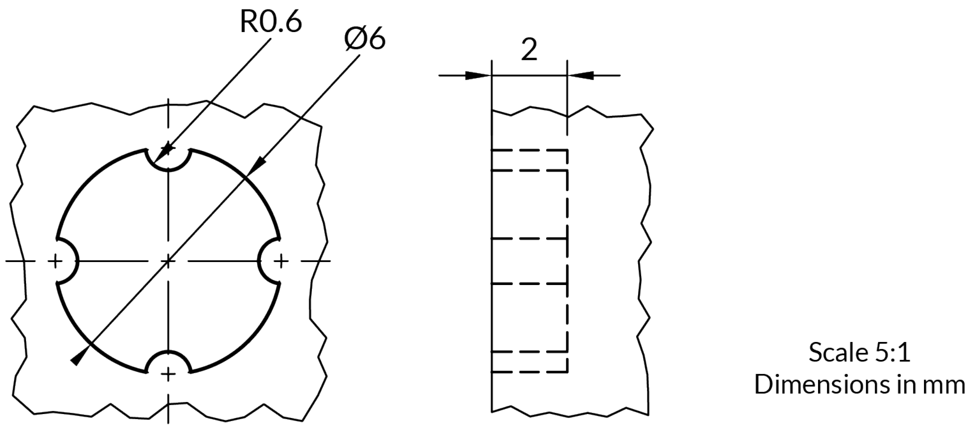


Figure 6.20 A technical drawing of the redesigned female 3D printed interface

Assembly Instructions

The programmatic aspects of the assemblability of the HP tool are managed within the *Brick Packing* and *Shell Decomposition* algorithms. The actual assembly has to happen in the physical world. While automated assembly is possible [154], [155], and can be LEGO compatible with the development of Autodesk's BrickBot capable of assembling simple structures [156], for the time being the assembly is 'human-actuated'.

The prototype assembly was straightforward with the smaller objects (e.g. computer mouse), however as the number of bricks and components increased it became significantly more difficult and time consuming to workout which bricks were needed where. Correspondingly, there needs to be instructions and guidance on which parts and LEGO bricks are need to create the prototype. Assembly instructions could help to reduce the fabrication time and complexity of assembly of the prototypes. However, this would need

[154] Gershenfeld, N. et al. (2015) *Macrofabrication with Digital Materials: Robotic Assembly*
[155] Langford, W. et al. (2016) *Automated Assembly of Electronic Digital Materials*
[156] Terdiman, D. (2018) *Autodesk's Lego model-building robot is the future of manufacturing*

to be measured through user testing to quantify the reduction in fabrication time with different forms of assembly instructions.

These instructions were implemented as a slider in the HP tool that the designer could move to show the different parts needed to assemble the prototype. Figure 6.21 shows four stages of the assembly process.

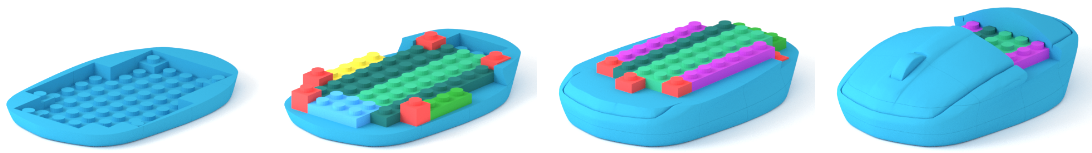


Figure 6.21 Images showing assembly stages of the computer mouse

6.6 Concluding Remarks

This chapter has shown how Hybrid Prototyping can be implemented in practice through the development of the DfFA rules and their subsequent integration into the HP tool. The tool was then evaluated in the case studies, from this further refinements were enacted and improvements posited. Therefore, this chapter answered the second research question of how to practically implement HP. However, the answer to RQ2 is specific to using LEGO and 3D printing HPs, with the DfFA rules and algorithmic approach implementing the particular constraints of the construction kit and printers.

The overall capability of HPs was evidenced through the creation of assemblable prototypes. However, as the fabrication time results did not meet those found in Chapter 5, more research is required to realise and maximise the findings. The advanced process considerations and improvements posited are investigated in Chapter 7.

Chapter 7

Maximising Improvements

7.1 Overview

Chapter 5 demonstrated the feasibility and value of creating Hybrid Prototypes. Chapter 6 demonstrated the practical feasibility of using Hybrid Prototypes. However, there needs to be further investigation and tool development into how these results can be maximised. This chapter develops the strategies and optimisations to fulfil the third research question by building on the previous work documented in earlier chapters. Research Question 3 is:

> "RQ3: How can the improvements in fabrication time and reusability be maximised?"

From Chapter 6, three areas were identified as potential ways to improve the results of the Hybrid Prototyping tool. The three areas were as follows:

- Parallelisation and load balancing of fabrication of the prototype.
- Adapting the level of fidelity required from the prototype.
- Managing level of decomposition and LEGO usage in the prototype.

These arose from findings in the results, as well as the aspects of the Design for Fabrication and Assembly rules not addressed in the implementation of the HP tool.

Consequentially, this chapter starts by introducing and discussing potential strategies that could be employed to address the three areas identified. By addressing them, opportunities could arise for decreasing fabrication time or increasing reusability when creating Hybrid Prototypes. These strategies are drawn from a combination of existing approaches in literature and considerations that have arisen during the development of the Hybrid Prototyping tool. These strategies are interrelated and their mapping is discussed. From this mapping, a subset of strategies for each area is chosen to demonstrate their impact.

The next section then considers the application of the different strategies – i.e. how to implement them within the HP tool, along with some initial results. The strategies are then performed on the case study objects to show how the benefits of Hybrid Prototyping can be realised. The chapter concludes by discussing the results and identifying the key findings.

7.2 Potential Strategies

There are many approaches to addressing each of the three areas introduced in Section 7.1. The overall objectives of the strategies is to either reduce fabrication time or to increase reusability, though these are not mutually exclusive. Table 7.1 gives a brief overview of the strategies and their objectives. Figure 7.1 shows how these strategies map to the three areas and how they interrelate.

The key interrelationships in Figure 7.1 that affect all three areas are:

Table 7.1 The description of the strategies and their objectives

Strategy Name	Description	Objective Fab. Time	Objective Reuse
Parallel Printing	Distributing the printing over multiple printers	●	
Load Balancing	Individual parts have similar print times	●	
Sub-Assemblies	Generate sub-assemblies that can be assembled separately	●	◐
Shell Decomp.	Altering how and where the shell is decomposed to be printed	◐	●
Standard Parts	Ensuring best use of standard parts (LEGO bricks usage and approximation of generic printed parts)		●
Granularity	Size and number of resultant parts	◐	●
Feature Decomp.	How features are split up for reuse		●
Feature/Region Preservation	How features/ROIs are chosen and kept at high fidelity	●	
Vary Fidelity	How the fidelity is varied across the prototype (use of LEGO bricks, approximating geometry, or reduce surface detail)	●	

- The decomposition of the prototype geometry - in particular the granularity and feature decomposition and how that affects the parallelisation and fidelity of the prototype.
- The usage of standard parts (LEGO bricks or 'custom' standard printed parts) to enable the creation of sub-assemblies and reduce the fidelity but increase the reusability.

A secondary interrelationship identified is that approximating geometry to generate standard parts would also impact the fidelity of the prototype. In all cases there is a trade-off in the relationships between reducing fabrication time, increasing reusability, and specifying the required levels of fidelity – decisions the designer would have to make during the design and prototyping processes.

7.2.1 Choice of Strategies

As Table 7.1 shows there are several strategies (some of which can be broken down into sub-strategies) that could be implemented to maximise the benefits of Hybrid Prototyping. As it is not possible to investigate them all, this section chooses the strategies to consider in the case study objects in Section 7.3.

A Hybrid Prototype results in a prototype that has the majority of its volume occupied

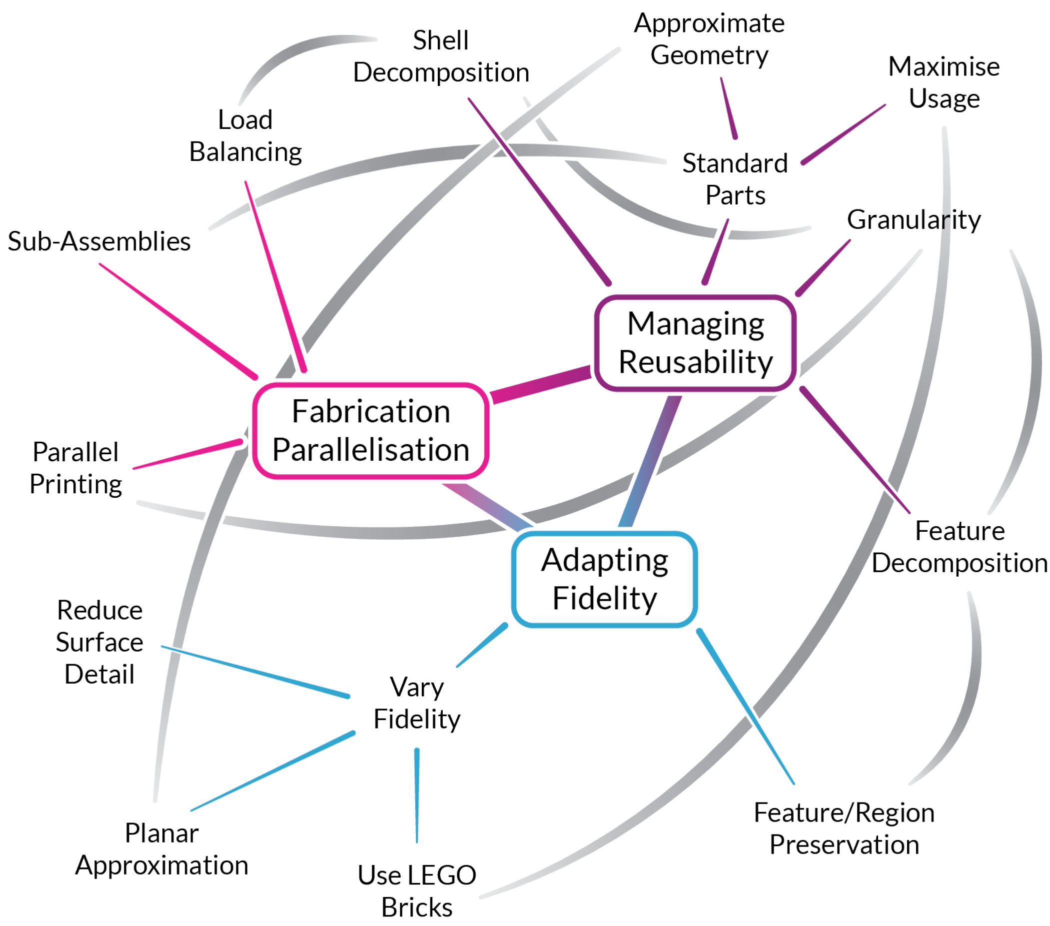


Figure 7.1 Mapping between the areas for improvement and potential strategies

by LEGO. Despite this, the greatest proportion of the fabrication time arises from the time taken to print the parts, rather than assemble it together. It follows that in order to maximise the fabrication improvements of HP, the strategies should focus on how to manage and reduce the 3D printing requirements rather than reducing the assembly time. As a result, the strategies can reduce the printing component of the fabrication time either by reducing the number and size of parts that have to be printed or by distributing the printing over multiple printers.

Improving the reusability of the prototype would lead to less material usage and lower prototyping costs. The strategies considered in this chapter will focus on how the LEGO usage can be maximised and how printed parts could be reused. However, reusing printed parts that have been modified into standard parts through the approximation of local geometry is not considered as it is out of scope of this thesis.

From the list in Table 7.1 strategies were chosen for each of the three areas. These strategies form a natural continuation of the tool development to this point and so are viable ways to maximise the benefits and improvements when creating Hybrid Prototypes. These are as follows:

- *Vary Fidelity through Feature Preservation* – key regions of interest on the prototype are 3D printed high fidelity parts, with the rest of the geometry constructed out of LEGO.

- *Parallelisation of Printing* – distributing the 3D printing across multiple printers.
- *Standard parts and maximising Usage* – adjusting LEGO structure and usage, as well as the modularity of the printed parts.

The following sections described each of these in more detail.

7.2.2 Adapting Fidelity HP

The adapting fidelity strategy aims to improve the fabrication time of the prototype by reducing the number of printed parts and amount of printing required. This is achieved by selecting regions of interest (ROI) in the design geometry that the designer intends to evaluate. These regions are then printed and assembled together with the LEGO bricks to form the prototype. The benefit is that the approximate overall form of the prototype can be constructed quickly out of LEGO, with only a small amount of 3D printing required to have high fidelity.

The concept for adapting the fidelity of a Hybrid Prototype stems from Camburn *et al.* [12] who suggest *subsystem isolation* as a way to reduce the required prototyping efforts. In this case, the subsystem is the aspect or region of the prototype the designer is interested in, and the isolation focusses the fabrication efforts on creating the high fidelity parts required for those regions. Similarly, McCurdy *et al.* [79] introduced the concept of prototypes that are simultaneously high fidelity in some aspects, and low fidelity in others, stating that:

> "optimal prototypes would have mixed fidelities."

Fidelity was first defined and discussed in Section 2.2.2. In the case of the Hybrid Prototyping tool, the definition of fidelity will align with the conventional meaning of the level of visual representation of the design.

This approach has been used in several examples from literature:

- Wireprint [108] – 3D prints a low fidelity sparse wire mesh of an object, with solid printing for high fidelity regions.
- Fabrickation [54] – Uses LEGO bricks for low fidelity regions, with high fidelity 3D printed parts for interfacing parts.
- Platener [110] – laser cut sheets for the low fidelity parts, and 3D printed parts for the high fidelity, complex parts.

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[12] Camburn, B. et al. (2017) *Design prototyping methods: state of the art in strategies, techniques, and guidelines*
[79] McCurdy, M. et al. (2006) *Breaking the Fidelity Barrier - An Examination of our Current Characterization of Prototypes and an Example of a Mixed-Fidelity Success*
[108] Mueller, S. et al. (2014) *WirePrint: 3D Printed Previews for Fast Prototyping*
[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*
[110] Beyer, D. et al. (2015) *Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates*

However, while these examples demonstrated the functionality of the tools created, there was little consideration into characterising how the tools could be used, and the identification of regions of interest and their selection for processing.

Regions of Interest

The key aspect of this strategy is selecting the regions of interest that are to be kept high fidelity. These regions could include design features; handles, buttons, or other tactile elements that the designer may want to evaluate, or aspects of the design that have to fit/interface with other components.

The choice and selection of these different geometries is highly dependent on the product being prototyped, the stage of the design process, and the designer's intent for the design iteration. It follows that it is difficult to automatically predict the regions the designer is interested in evaluating. Consequentially, the process of mapping design intent to regions of interest, and predicting that decision, are out of scope of this research.

The implication is that there has to be a user-in-the-loop, manual process where the designer has to select the regions there are interested in fabricating at a high fidelity. The existing examples of mixed-fidelity fabrication [108], [54], [110] all used 'brush-like' tools for the user/designer to paint the surface of the 3D object to select the regions of interest. This approach gives the designer the freedom to select the regions that meet their requirements for each prototype instantiation.

An alternative option for selecting the desired geometry could be to choose particular design features. This would simplify the user interaction with the tool but would require knowledge about the structure of the prototype and the delineation of features. This type of design feature partitioning of 3D has been developed by Hao *et al.* [157]. From the segmented model the chosen regions can be selected for high fidelity printing.

Measuring Fidelity

In order to measure the impact of adapting the fidelity of a hybrid prototype, the level of fidelity needs to be calculated. This will allow comparisons of the fabrication times between prototypes with differing levels of fidelity.

This measure will provide a value of the proportion of the Hybrid Prototype that is high fidelity versus low fidelity, expressed as a percentage. The proportion can be based on the surface area of the target geometry – i.e. percentage of the surface that will be fabricated at a high fidelity level.

It could also be calculated from the proportion of features of a design that are high fidelity. However, this requires information about the features and the structure of the

[108] Mueller, S. et al. (2014) *WirePrint: 3D Printed Previews for Fast Prototyping*
[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*
[110] Beyer, D. et al. (2015) *Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates*
[157] Hao, J. et al. (2011) *An efficient curvature-based partitioning of large-scale STL models*

prototype. Consequently, it is difficult to for this approach to provide a measure that can be compared across different prototypes. Therefore, a surface area based approach will be more suitable for investigating adapting the fidelity of prototypes.

7.2.3 Distributed Fabrication HP

With 25 % of companies interviewed investing over $100 000 in 3D printing in 2019 [158] and the increasing prevalence of Fablabs (Fabrication Laboratory) across the world [159] has resulted in designers and engineers having access to multiple 3D printers. For example, Figure 7.2 shows 12 Ultimaker FDM 3D printers at the University of Bristol FabLab that are used by students and staff.

Figure 7.2 12 Ultimaker 3D printers at the University of Bristol FabLab

This availability of printers can be leveraged to distribute the printing of the Hybrid Prototype parts across multiple printers. Gopsill and Hicks [160] investigated the effect of scale and scheduling strategies when using multiple printers as an on-demand managed print services. This assumed that individual prints were submitted by users over the course of the day and tried to maximise the productivity and throughput of the service as a whole. For the fabrication distribution of HP, a different approach is required that considers how all the necessary parts for one prototype instance can be printed in the shortest time frame possible.

Cheng and Sin [161] considered multiple-machine scheduling theory as:

[158] Sculpteo. (2019) *The State of 3D Printing*
[159] FabLabs.io *FabLabs*
[160] Gopsill, J. A. and Hicks, B. J. (2018) *Investigating the effect of scale and scheduling strategies on the productivity of 3D managed print services*
[161] Cheng, T and Sin, C. (1990) *A state-of-the-art review of parallel-machine scheduling research*

> "the study of constructing schedules of machine processing for a set of jobs to ensure the execution of all jobs in the set in a reasonable time frame."

They identified three issues that need to be dealt with:

- Which jobs to be allocated to which machines?
- How to order the jobs in an appropriate processing sequence?
- How to rationalise the 'reasonableness' of the schedule?

As process scheduling optimisation is out of scope of this thesis, several assumptions have been made to reduce the complexity of the system. These assumptions are:

1. Overall print time is the only consideration; power consumption, up-time are out of scope.
2. All the capabilities are identical across all printers.
3. All print settings are identical across printers and parts.
4. The availability of the printers does not change due to maintenance, failure, or use from others.
5. There is no time difference between printing parts on one printer sequentially or all together.
    a. Tools, such as Packmerger [149], minimise required support material and travel moves when combining multiple parts in one print volume, therefore reducing the difference when printing sequentially.
    b. There is no down time between sequential prints on the same printer. While part removal is typically a manual process, either automated part removal [162] or rapidly swappable build plates [163] can be used to make this time negligible.
6. Only one prototype instance is required at one time – i.e. only the parts required for that instance have to be considered for scheduling.

These assumptions help address the issues identified by Cheng and Sin [161]. Assumptions 2 to 4 mean that it is inconsequential which printer fabricates which part. Assumptions 5 and 6 imply that the sequence order of the prints does not affect the overall print time. It also implies that overall print time does not change if the prints are packed into the print volume (i.e. [150]) or limited to one at a time (i.e. [151]). Finally, Assumption 1 states that the schedule only needs to be rationalised by how long it takes to print all the required parts.

The implication of these assumptions is that the parts can be scheduled to minimise the overall print time with only the number of printers and the list of part print times required. This makes the problem a bin packing problem - i.e. with a specified, fixed number of printers (the bins), how can the individual part print times (the items) be

[149] Vanek, J. et al. (2014) *PackMerger: A 3D print volume optimizer*
[162] Blackbelt 3D BV. (2018) *Blackbelt 3D Printers*
[163] Schwartz, J. (2017) *How We're Building a Robotic 3D Printing Factory*
[150] Yao, M. et al. (2015) *Level-set-based partitioning and packing optimization of a printable model*
[151] Oh, Y. et al. (2017) *Part Separation Methods for Assembly Based Design in Additive Manufacturing*

distributed across the printers such the bins are approximately equal in length (or such that the longest bin is minimised)? This problem has some well established algorithmic solutions that can be leveraged for this situation [164].

The parallelisation (and balancing) of the printing can be achieved in two ways:

- *Distributing* – Distributing the outputted part times across multiple printers with no consideration to the spread/length of print times.
- *Load Balancing* – Adapting the size of the resultant parts from the *Decomposition* algorithm (see Section 6.4.3) to better balance the print times across multiple printers and reduce their spread.

These approaches are covered in the following sections.

Distributing

The simplest way to distribute the printing of the Hybrid Prototype is to spread the parts over a predetermined number of printers. This uses bin packing to determine how the subsets of parts should be sorted – i.e. which printer gets which group of parts to print. Figure 7.3 illustrates this with three printers each with a different group of parts with varying print times.

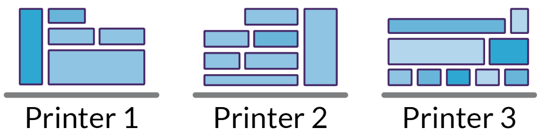


Figure 7.3 An illustration of parallelising the printing through bin packing the print times across multiple printers

Based on the assumptions established previously, the overall print time to produce all the required parts is the single printer which has the longest print time as the shorter bins will finish before it. Therefore, the aim is to equalise the print times across the printers as best as possible.

However, due to the variance of individual print times for the HP parts, it may not be possible for the bin packing to create closely matched times - resulting in a sub-optimal print time. This is one of the issues of taking the *decomposition* algorithm output with no consideration to the shape, size and print time of the parts.

Load Balancing

Load balancing builds on the idea of distributing the printing, however in this case, the geometry of the printed parts is modified at the *decomposition* algorithm stage. This allows the individual part print times to be equalised and matched to the number of available printers by changing how the hollow shell geometry is decomposed. Once decomposed, the bin packing is applied in the same manner as Section 7.2.3.

[164] Martello, S. and Toth, P. (1990) *Knapsack Problems: Algorithms and Computer Implementations*

The benefits are that the total print times for each printer can be more closely matched resulting in an improvement in overall print time. Figure 7.4 illustrates how equal length print times can result in a more even packing of the printers.

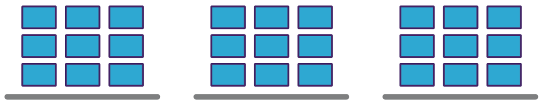


Figure 7.4 An illustration of load balancing the printing by more evenly decomposing the printed parts to distribute over multiple printers

In practice, load balancing of individual parts is much harder to achieve as the assembla-bility constraints of the DfFA rules forces the shell to be decomposed in particular ways that may result in imbalanced print times. This makes the problem over-constrained and requires input from the designer to decide which rules to relax. Consequently, the load balancing will not be applied to the case studies in Section 7.3.2.

7.2.4 Reuse Focussed HP

One of the benefits of Hybrid Prototyping is the ability to reuse parts. As shown in Chapter 5, the LEGO based level of reusability is dependent on the size of the bricks used. However, this only considers the LEGO bricks being reused. Here, the definition of reusability was the proportion (by volume) of the prototype that was constructed out of LEGO. This definition needs to be expanded to include the potential reuse of printed parts. As the *decomposition* algorithm creates LEGO compatible parts there are opportunities to be able to reuse them to save further time and material.

There are several approaches to managing the reusability and material usage of the resulting Hybrid Prototypes. These can be split into two areas:

- Single prototype instance – considering one prototype in isolation.
- Between prototype iterations – considering how the prototypes change between iterations.

In both cases the LEGO usage and the printed parts need to be considered. One approach that applies to both cases, is to create a hollow LEGO structure. Testuz *et al.* [165] investigated this approach to optimise and reduce the number of LEGO bricks required to make 3D objects whilst keeping them structurally stable, helping reduce the assembly times This benefit would scale with the size of the prototype (and therefore number of LEGO bricks) – i.e. the larger the object the greater opportunity for hollowing the structure and removing bricks. However, using a hollow structure would limit the use of the existing reusability metric as it is based on the volume of the LEGO bricks and printed parts. As a result, a new metric for considering the material usage would need to be calculated.

Further approaches that fit into the two categories are discussed in the following sections.

[165] Testuz, R. et al. (2013) *Automatic generation of constructable brick sculptures*

Single Instance

The single instance approaches consider how to achieve 'generic' reuse where the structure, geometry and size of subsequent uses is unknown. The reuse could be in another iteration of the same design or in a completely different design. Therefore, parts have to be able to be reused in any situation.

The simplest way to increase the reusability of a single HP instance is to maximise the LEGO use within the geometry. This is achievable if the size of the bricks can be scaled to match the optimum (i.e. use Nano bricks, DUPLO, or create a bespoke sized construction kit) However, this is not feasible due to availability of parts or time to create bespoke kits and the optimum scale is likely to change when designing a different product.

For the examples in this thesis LEGO bricks are used. In order to maximise their usage it is key that the smallest parts are used (i.e. 1×1 plate) to better approximate the geometry and ensure that the greatest proportion of the prototype can be reused.

Due to the LEGO bricks' standard dimensions, it is trivial to see how they could be reused in another design or iteration. However, it is not as straightforward to reuse the 3D printed parts - mostly due to the fact they embody particular geometry or features that are specific to that HP instance. This means that parts can only be directly reused if its geometry matches that required in the other instance.

Printed parts can be reused if their shape is generic enough to match different geometries. In order to create more generic geometry the *decomposition* needs to create numerous, small printed parts that discretise the curves and edges of the parts. These could then be recombined into new and different geometry. Two issues arise from this:

- The greater surface area and part count of smaller parts results in a longer fabrication time in both printing and assembling.
- The increased number of parts each with small variations makes it challenging to identify and use suitable parts to realise the new geometry.

Therefore, there is a trade off when considering HP instances in isolation. The designer must decide whether increased reusability is worth the penalty of increased fabrication time.

Between Iterations

The between iterations approach considers how to maximise the reuse of parts between subsequent (not necessarily sequential) iterations of the same design.

A key part of this is ensuring the orientation of iterations is maintained. Mueller *et al.* [54] mention an approach for matching orientation between similar design iterations. This ensures the underlying LEGO structure maps between iterations, this brings two benefits:

- The core LEGO structure does not have to be fully disassembled between iterations -

[54] Mueller, S. et al. (2014) *faBrickation : Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*

only the bricks that have changed (added/removed) need to be assembled.

- In the case of minor changes, the new printed parts can be assembled onto the existing prototype's LEGO structure. This also means that only the printed parts that have changed between iterations need to reprinted, significantly improving the reusability (all the unchanged parts can be reused) and reducing the overall print times.

Both of which result in shorter fabrication times for later HP iterations. However, as the position of the LEGO structure needs to be fixed between iterations, it may not result in the optimal brick packing for a particular iteration. This is a trade-off between reduced single iteration reusability and increased reusability (and reduced fabrication time) across the design iterations.

Another approach to improving the reusability between iterations is to ensure the interchangeability of parts. This would allow features to be isolated and be swapped out between design variations/iterations – i.e. different handles that could be swapped out without affecting or altering the bulk of the prototype. Duncan *et al.* [166] investigated achieving this in models of animals, adding the ability to swap different parts onto different bodies. They used mesh analysis to ensure continuity between different parts, before creating the necessary geometry decompositions.

Applying this approach would mean that a prototype can have a high reusability (most parts and all LEGO being reused), while still being able to investigate multiple design iterations. It would also allow the designer to easily retrace their steps to an earlier version of the design. The caveat is that this only works when designing or evaluating individual features. The concept could be extended to ensure continuity is maintained at each part boundary. However, this would require the prototype's decomposition to be fixed between iterations so that part boundaries do not change. This integrates well with the Adapted Fidelity strategy identified in Section 7.2.2, isolating the designer's key areas.

7.3 Investigating Strategies

In this part of the chapter, the strategies chosen in Section 7.2 are investigated and their impact on Hybrid Prototyping reported. The three strategies are:

1. Adapted Fidelity HP
2. Distributed Fabrication HP
3. Reused Focussed HP

The following sections address each of these in turn.

[166] Duncan, N. et al. (2016) *Interchangeable components for hands-on assembly based modelling*

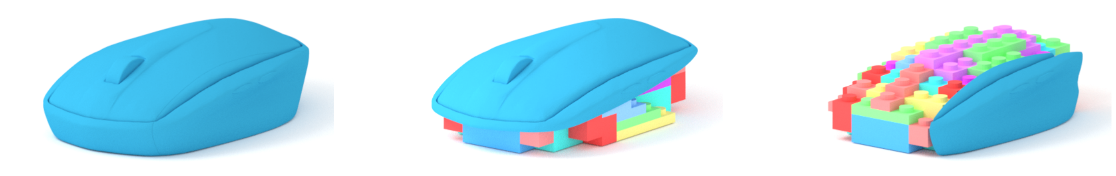
7.3.1 Adapted Fidelity HP

The first strategy investigated is adapting the fidelity of the Hybrid Prototype to reduce the amount of printing required. This is achieved by preserving fidelity in key regions of interest (ROI). The ROIs are printed parts with LEGO making up the rest of the prototype. As the ROIs would vary with design intent, it is impossible to predict, and therefore automate, their locations. As a result, the ROIs were manually selected for the study report in this section.

The method is described, before presenting the results and discussing the key findings.

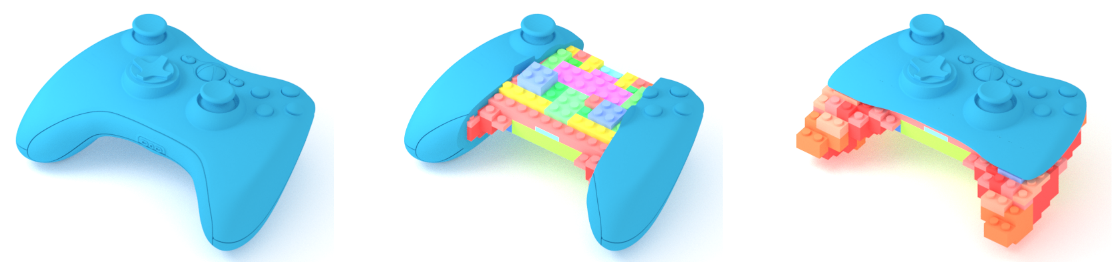
Method

For each of the case study objects, three levels of fidelity are considered: full fidelity (i.e. a standard HP), a medium fidelity, and a low fidelity prototype. This study will only consider using a single printer and will allow the full library of LEGO bricks to be used – ensuring the only independent variables varied are the object and fidelity level. Figures 7.5 to 7.7 show the three levels of fidelity for the three objects. The regions were selected for two design scenarios: considering user interaction and ergonomics, and considering button and control positions.



(a) Full fidelity (b) Medium fidelity (c) Low fidelity

Figure 7.5 The three levels of fidelity for the computer mouse

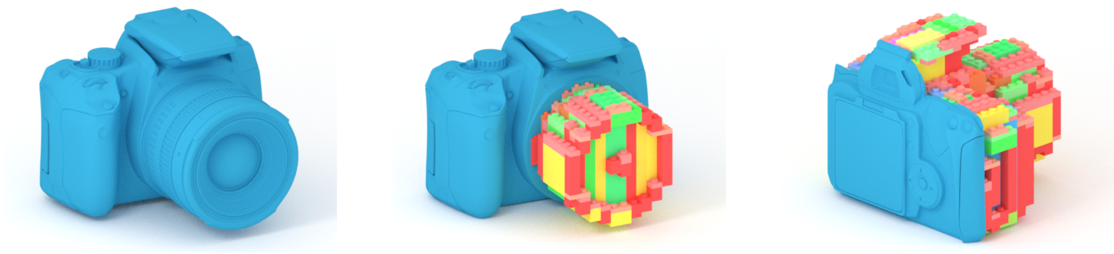


(a) Full fidelity (b) Medium fidelity (c) Low fidelity

Figure 7.6 The three levels of fidelity for the video game controller

For the results the level of fidelity was measured as the percentage of outside surface area that is printed. This allows comparisons to be drawn between the different objects. Equation 7.1 shows the calculation for the measure of fidelity

$$F = \frac{A_r}{A_o} \times 100 \qquad 7.1$$



(a) Full fidelity (b) Medium fidelity (c) Low fidelity

Figure 7.7 The three levels of fidelity for the digital camera

where F is the measure of fidelity (expressed as a percentage), A_o is the original surface area of the object, A_r is the external surface area of the printed parts for the reduced fidelity prototype. Table 7.2 shows the fidelity measures for each of the objects and the level of fidelity.

Table 7.2 The fidelity measures for the three objects at each level of fidelity

Object	Full / %	Medium / %	Low / %
Computer Mouse	100.00	50.06	24.03
Video Game Controller	100.00	63.87	30.65
Digital Camera	100.00	67.77	20.94

Results

Figure 7.8 shows the fabrication times for the three levels of fidelity for the three case study objects. The time taken to print the object as a single part is also plotted. The results show that the fidelity has to be reduced in order to fabricate prototypes faster than purely printing them.

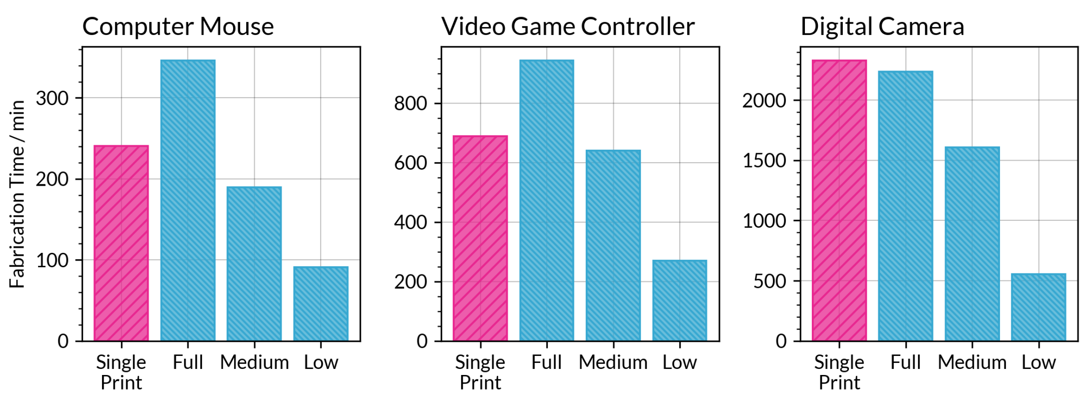


Figure 7.8 The fabrication times for the three level fidelity for the three case study objects

Figure 7.9 shows the relationship between fidelity and the percentage reduction in fabrication time. A linear regression has been fitted, and from this the fidelity needs to be at most 78.7 % to match the print times of a single part. Similarly, to meet the fabrication time reduction (of 45 %) set out in Chapter 5 the level of fidelity needs to be 41.3 %.

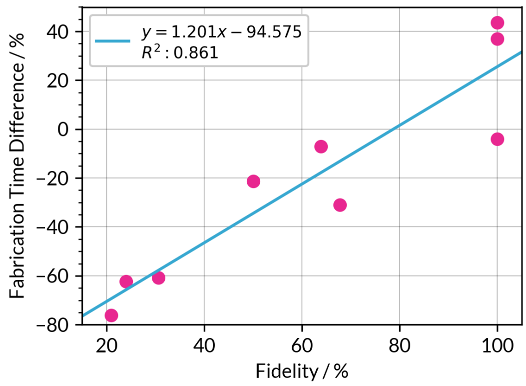


Figure 7.9 The difference in fabrication time when adapting the fidelity against a single print

Key Findings

The key findings from the investigation into preserving selected regions of interests are summarised in Table 7.3.

The first finding is the relationship between the level of fidelity and reduction in fabrication time. It was apparent that as the level of fidelity decreased the so did the prototype fabrication time. This was the expected result, however the data allowed the relationship to be quantified. Figure 7.9 shows the linear relationship.

As stated earlier in this chapter, the goal of the strategies investigated was to better (or meet) the results set out in Chapter 5 where the potential benefits of HP were initially characterised. This leads to the second finding; in order to meet the 45 % reduction in fabrication time, the fidelity needs to be reduced to 41.3 %. Presenting this measure to the designer while they are selecting ROIs could help inform them about how their decisions could affect the fabrication time.

Table 7.3 The key findings from investigating Adapted Fidelity HP

Finding	Description
Fidelity vs Fabrication time	A reduction in fidelity leads to a reduction in fabrication time.
Comparison against simulation	A fidelity level of 41.3 % is required to match the simulation results of 45 % reduction in fabrication time.

7.3.2 Distributed Fabrication HP

The distribution of the 3D printing was investigated by using the results from the iterations of the case study objects in Chapter 6. The following sections describe the method, results and findings of varying the number printers used to print the required parts for a particular instance of a hybrid prototype.

Method

A computational approach was used to simulate the effect of distributing the printing times for the parts of a hybrid prototype across increasing number of printers.

The data recorded in the simulations reported in Chapter 6, included the individual print times of each individual constituent part for a single Hybrid Prototype for each object, iteration, and number of vertical cuts. The number of printers ranged from 1 to 20. As mentioned in Section 7.2.3, a bin packing algorithm was used to attempt to evenly distribute the part print times across a fixed number of printers. With the overall print time being the total print time of the longest printer. Therefore the overall fabrication time is give by Equation 7.2.

$$T_f = \max_{n \in N} \sum_{i \in P_n} P_{n\,i} + T_a \tag{7.2}$$

where T_f is the fabrication time, T_a is the assembly time, N is the number of printers, and $P_{n\,i}$ is an individual part print time associated with printer n.

The longest print time relies on the bin packing algorithm to sort the part print times. This employs a greedy algorithm that puts each part time (in decreasing size order) into the printer with the shortest total print time. This is repeated until all the part times have been allocated. Figure 7.10 shows a simplified case of this algorithm with two printers.

```
def binpacking(part_times):
    "returns: An attempt at bin packing of 'part_times'
    into two sets of equal sum"
    printer_1 = []
    printer_2 = []
    sorted_part_times = sorted(part_times, reverse=True)
    for n in sorted_part_times:
        if sum(printer_1) < sum(printer_2):
            printer_1.append(n)
        else:
            printer_2.append(n)
    return (printer_1, printer_2)
```

Figure 7.10 The bin packing algorithm for the simple case of two printers

The bin packing algorithm is applied to the data, varying the number of printers from 1 to 20. This lends itself to the simulation-based approach as it calculations are deterministic and need to be performed for a large number of variables.

Results

Figures 7.11 to 7.13 show how the fabrication times vary as the number of printers increases for the iterations for each of the case study objects. Each line represents a different number of vertical cuts (and therefore, different number of parts). In all cases, there comes a point where adding more printers does not decrease the fabrication time.

Figure 7.14 shows the distributions of percentage differences between using a single printer and multiple printers – across all objects, iterations, and vertical cuts. Figure 7.14a

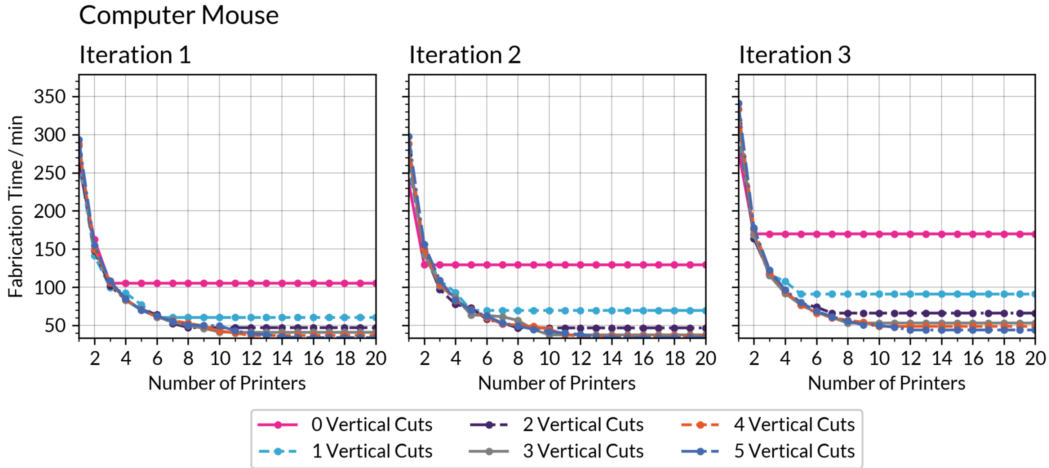


Figure 7.11 The fabrication times for the three iterations of the computer mouse for different numbers of printers

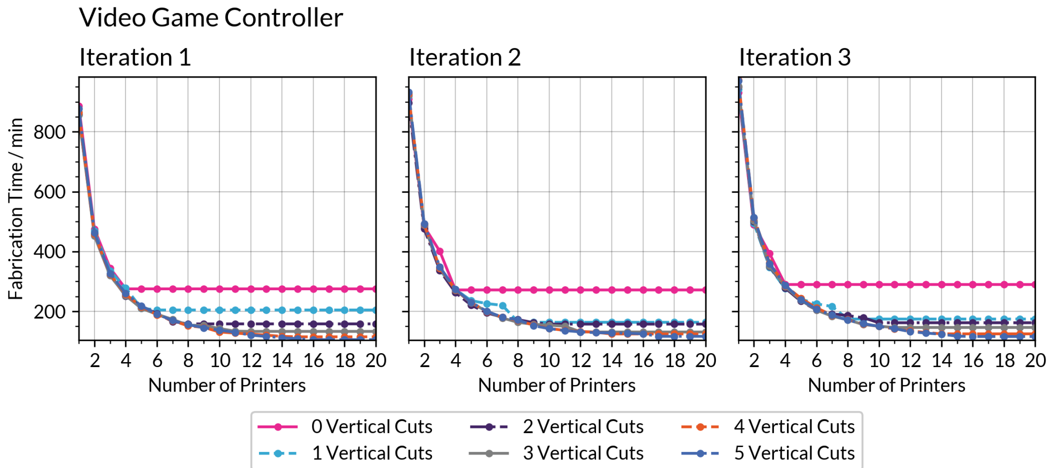


Figure 7.12 The fabrication times for the three iterations of the video game controller for different numbers of printers

considers the fabrication difference using Hybrid Prototyping with a single printer, while Figure 7.14b considers printing the prototype as a single part. In both cases the difference is compared against using Hybrid Prototyping with multiple printers. These plots clearly show the significant benefits of going from 1 to 2–6 printers, and the diminishing benefits of using more than 8–10 printers. Figure 7.14b shows that in order to achieve the results reported in Chapter 5 of 45 %, then at least 3 printers are required to have a mean reduction in fabrication time of 47 %.

Figure 7.15 shows the number of printers required to minimise the fabrication time for different numbers of printed parts. As expected, as the number of parts increase the optimal number of printers required increases. This does not take into account differing size or print time of the individual parts.

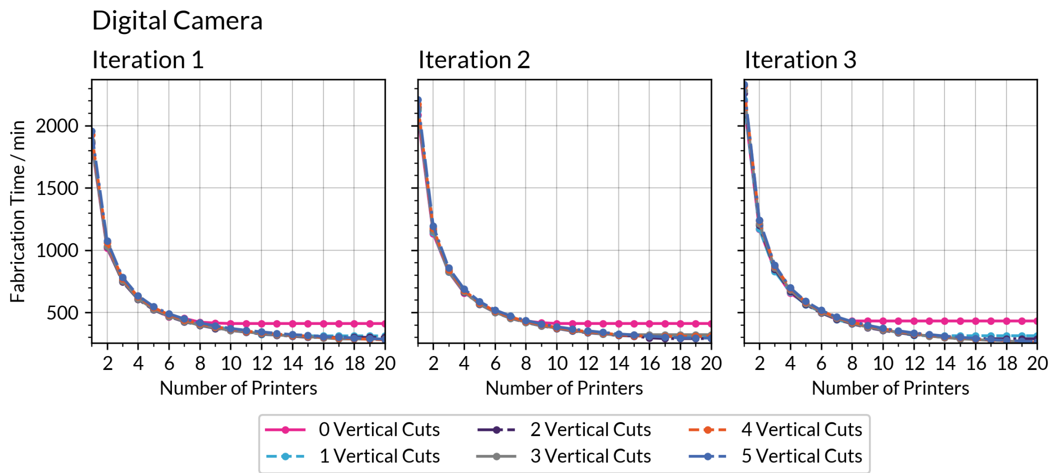
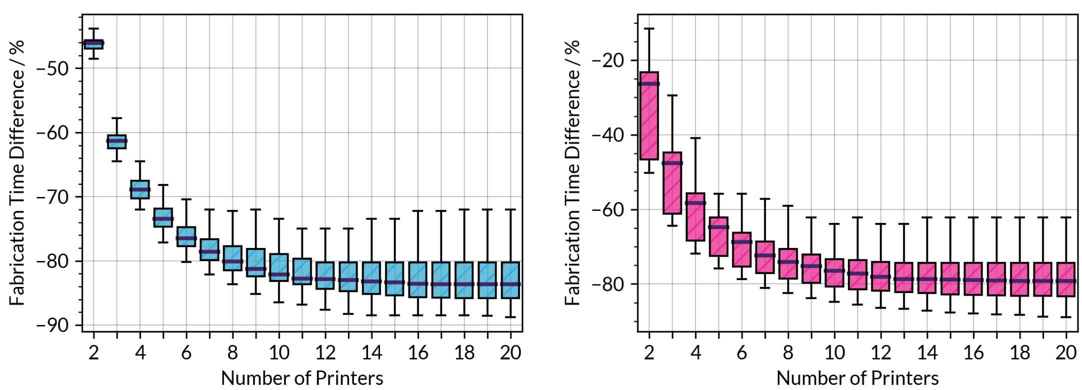


Figure 7.13 The fabrication times for the three iterations of the digital camera for different numbers of printers



(a) Using Hybrid Prototyping

(b) Single-part prototype

Figure 7.14 The percentage difference in fabrication time when using a single printer with Hybrid Prototyping and printing the prototype as a single part

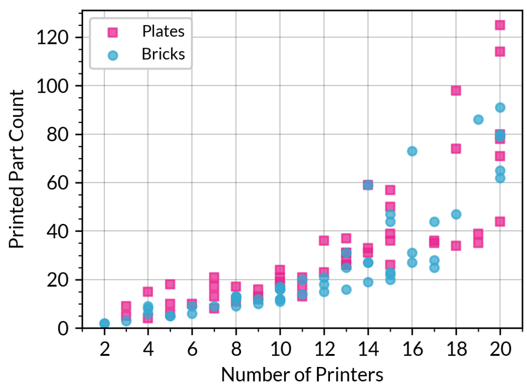


Figure 7.15 The number of printers required to minimise the fabrication time for different number of printed parts

Key Findings

The key findings from investigating the effect of distributing the fabrication required in Hybrid Prototyping are summarised in Table 7.4.

The first finding is that there is diminishing returns when using more than 10 printers (see Figure 7.14). With the most benefit realised by increasing the number of printers used from 1 to 2–6.

Figure 7.14b shows the number of printers required to match the simulation results of a 45 % reduction in fabrication time (see Chapter 5). Therefore, the second findings is that at least 3 printers are required to achieve a mean reduction of 47 % or 5 printers to guarantee exceeding the results.

The third finding is that as the number of parts increase, the number of printers necessary to minimise the fabrication time increases. However, this needs to be considered in the context of Figure 7.14a. While 20 printers may result in the minimum print time for the number of parts, it is unlikely to be significantly faster than using 15, or even 10, printers - particularly considering the capital and running costs of deploying more printers. This is an aspect that the designer would need to consider when using the Hybrid Prototyping tool.

Table 7.4 The key findings from investigating Distributed Fabrication HP

Finding	Description
Number of Printers	Diminishing reduction in fabrication time beyond 10 printers.
Comparison against simulation	At least 3 printers are required to meet the simulation results of 45 % reduction in time.
Number of Parts	As the number of parts increases so does the number of printers required to minimise fabrication time.

7.3.3 Reuse Focussed HP

The final strategy investigated for maximising the benefits of Hybrid Prototyping was considering how to maximise part (both LEGO and printed) reuse between iterations. The key objective is to generate the Hybrid Prototype in such a way that only the modified aspects of the design's geometry are reprinted and reassembled.

This strategy required further development of the Hybrid Prototyping tool to improve the between iteration part reuse. The developments were two-fold:

- Ensuring the LEGO array (c.f. Figure 5.3 and Equation 5.4) remained in a fixed position. This minimises the amount of LEGO disassembly/reassembly required to modify the prototype into the next iteration. It also prevents the printed part/LEGO interfaces from shifting, again maximising the number of parts that can be reused.

- Where possible, maintaining the location of the shell decomposition cuts. If these occur in the same location, then the boundaries between printed parts remain constant, ensuring that only the modified printed parts can be reprinted and assembled without impacting the surrounding, unchanged parts.

The first point was addressed by adding in a user interface toggle that tells the tool to store the LEGO array position and to use in subsequent Hybrid Prototypes. Normally, the tool shifts the array to find the best position (based on number of bricks used), providing a specific position for each different iteration or geometry. However, as this fixes the position of the LEGO array based on the first iteration, subsequent iterations may not have the optimal position.

The second point was achieved in a similar manner – the locations of the vertical planar cuts (first chosen by the user) were maintained between iterations. However, due to the assemblability constraint of the DfFA rules, the horizontal cuts could not be persisted as they ensured the prototypes could be assembled.

The following sections describe the method and results before presenting the key findings.

Method

The investigation into the reuse of parts between iterations focussed on two design iteration situations:

1. Large general changes that affect the whole prototype.
2. Small local changes that affect a small region of the prototype.

To address both cases, the three case study objects are used. For the first case, the design will progress from a simple form to a more detailed one, increasing in size and complexity. For the second case, the design will progress with a small localised geometry change with the rest of the prototype remaining constant. These changes are shown in Figures 7.16 to 7.18. The comparisons are drawn between Figures a and b, and b and c for the respective cases.

(a) Simple Form (b) General change (c) Localised change

Figure 7.16 The iterations changes for the computer mouse

This study only considers using a single printer and will allow the full library of LEGO bricks to be used. The only independent variables varied are the object geometry, level of changes, and number of vertical cuts (0–5 cuts).

(a) Simple form (b) General change (c) Localised change

Figure 7.17 The iteration changes for the video game controller

(a) Simple form (b) General changes (c) Localised changes

Figure 7.18 The iteration changes for the digital camera

In order to calculate the differences in parts required between iterations a comparison is made from the previous iteration to the next. For the LEGO, this is simply taking the two lists of required bricks and generating the differences between each type of brick. It is less straightforward to identify which printed parts are kept and which have to be reprinted. For this investigation, the surface area and volume of each part is compared and a threshold is used to determine whether the parts are the same. While it is possible that two parts have different geometries but the same surface area and volume, it is unlikely due to the constraints of the prototype geometry.

In each case of the study, the additional fabrication time and parts required to move from one iteration to the next is calculated. From this the level of reusability can be calculated. In all cases comparisons are made against using normal Hybrid Prototyping and printing the prototype as a single part.

Results

Figures 7.19 to 7.21 show a comparison of fabrication times between the start iteration and the next one for general and local changes, across the three case study objects. For the second iteration, the fabrication time when the reuse strategy is employed is plotted. The spread in fabrication times arises from the different number of vertical cuts.

The results show that for general changes there is very little benefit in ensuring reusability between iterations. However, for localised changes, there is a significant benefit in the reduction of fabrication time. The mean percentages differences between normal HP and reuse focussed HP are shown in Table 7.5. This shows that the mean difference for general changes is −2.00 %, and −43.36 % for localised changes.

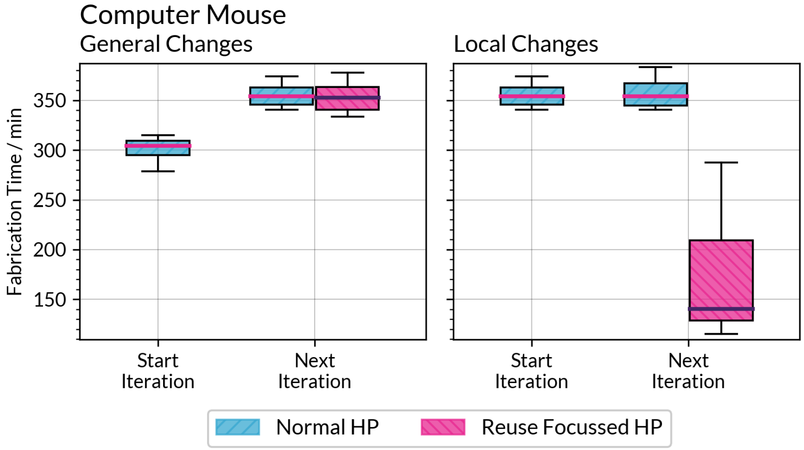


Figure 7.19 Comparison of the computer mouse fabrication time between iterations

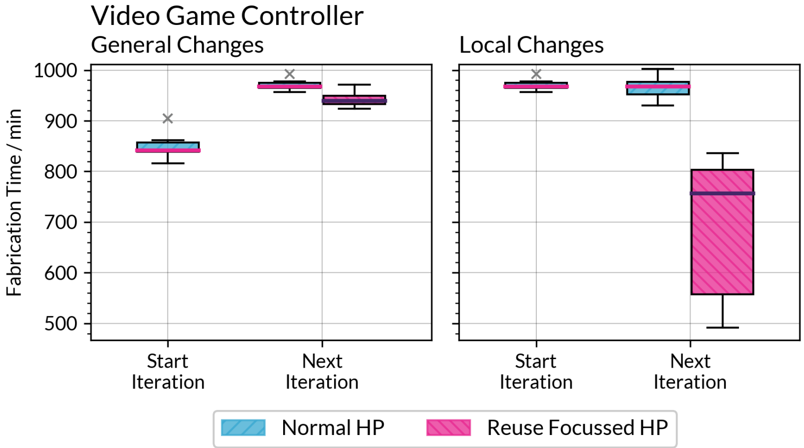


Figure 7.20 Comparison of the video game controller fabrication time between iterations

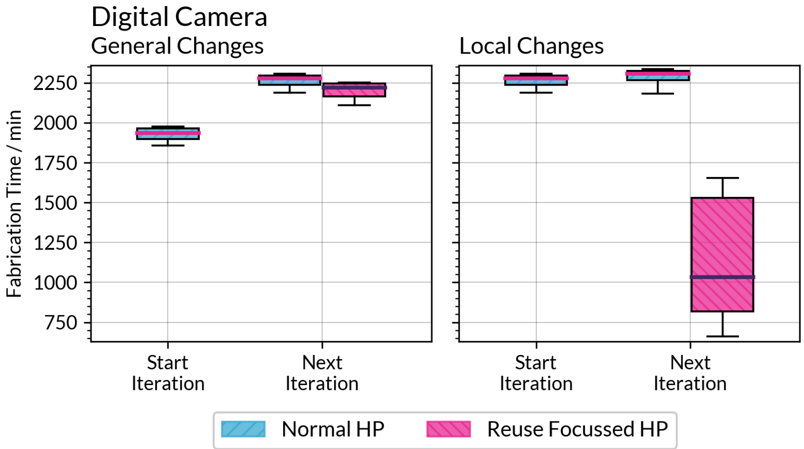


Figure 7.21 Comparison of the digital camera fabrication time between iterations

Figure 7.22 shows the cumulative fabrication times for the two iterations of general and local changes. Comparisons can be drawn between printing the prototype instances

Table 7.5 The mean percentage difference in fabrication time between normal HP and reuse HP

	General / %	Local / %
Computer Mouse	−0.56	−51.46
Video Game Controller	−2.70	−28.36
Digital Camera	−2.75	−50.26
Mean Difference	−2.00	−43.36

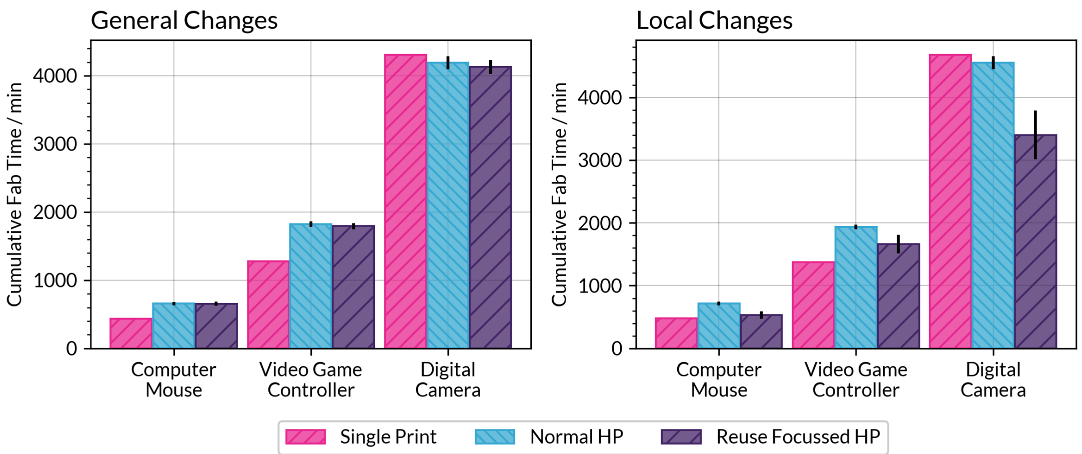


Figure 7.22 Comparison of cumulative fabrication time for two iterations when printing, HP, and reuse HP for general and local changes

as single parts, using normal Hybrid Prototyping and using reuse focussed Hybrid Prototyping. Over two iterations, it shows the total fabrication time is slower for the smaller objects (computer mouse, video game controller) than purely printing both iterations. However, the effect of reuse, particularly in design situations with local changes, should compound over further iterations, resulting in a shorter design process.

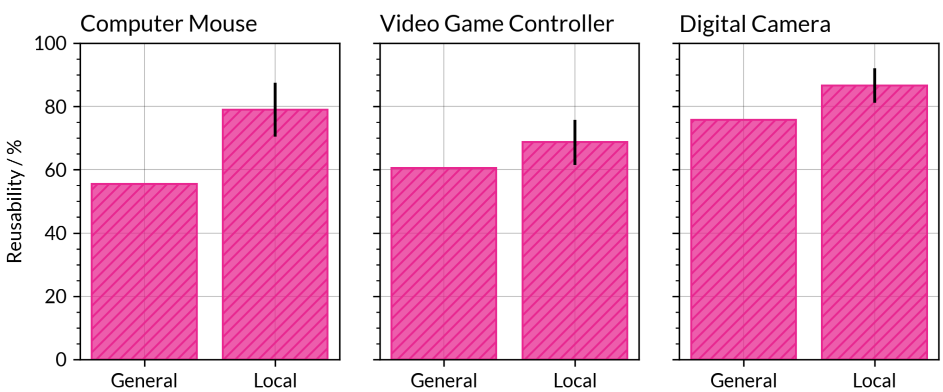


Figure 7.23 The mean percentage reusability of the three case study objects when performing general or local changes

Figure 7.23 shows the level of reusability (i.e. how much of the first iteration can be used in the next iteration) for general and local changes, for the three case study objects. As the plots show, there is a significant increase in reusability when dealing with more localised changes to the geometry. The results mean that there is less material wastage, and reduced fabrication times as parts can be reused instead of being reprinted.

Table 7.5 shows the mean percentage difference in reusability between normal HP and reuse HP. This shows that for general changes the reusability solely arises from the LEGO, while for local changes the increase in reusability can be attributed to more printed parts being reused between iterations.

Table 7.6 The mean percentage difference in reusability between normal HP and reuse HP

	General / %	Local / %
Computer Mouse	0.00	22.71
Video Game Controller	0.00	13.25
Digital Camera	0.00	13.34
Mean Difference	0.00	16.43

Figure 7.24 shows how the reusability of a prototype varies with the number of vertical cuts. For general changes, there is no variation in the reusability as all the printed parts have to be reprinted, and so the reusability is only arising from the LEGO. However, for local changes it shows that there is a positive correlation between number of vertical cuts and the level of reusability. Taking the number of vertical cuts as a proxy for number of printed parts (i.e. more vertical cuts results in more printed parts), this result is expected as the local changes are isolated to smaller parts requiring only the smaller parts affected requiring reprinting.

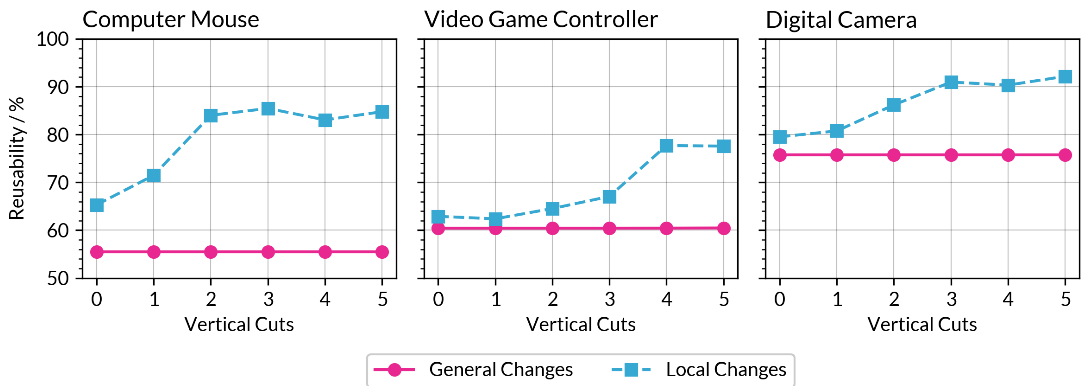


Figure 7.24 Plots showing how the number of vertical cuts affect the reusability of a prototype

Figure 7.25 shows this more clearly. For general changes, no printed parts are reused. However for local changes, the number of printed parts reused between iterations increases as the overall number of printed parts increases.

Findings

The key findings from the investigation into the iteration reuse strategy are outlined in Table 7.7.

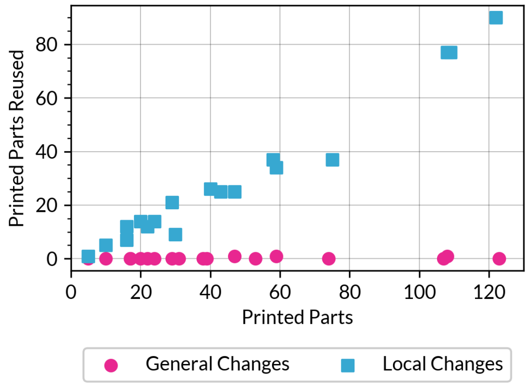


Figure 7.25 The relationship between the number of printed parts and number of printed parts reused

The first key finding is that the types of changes that occur between the iterations have an impact on the benefits of using a Reuse Focussed Hybrid Prototyping approach. For larger, general changes to the geometry there is little benefit to using a reuse approach. This only reduced the fabrication time by an average of 2.00 % with no improvement in reusability. Due to the large changes, most, if not all, the printed parts required reprinting for the next iteration and so it was no different to using the normal HP approach. In the iterations with small geometric changes, there were many parts that could be reused in the next iteration (due to the localised nature of the changes only some printed parts were affected). Here there was a significant improvement over normal HP, with a 43.36 % reduction in mean fabrication time and a 16.43 % increase in reusability.

The second finding is that the number of vertical cuts (and by extension, the number of printed parts the shell was decomposed into) affected the reusability of the prototype. This was apparent in the iterations with local changes, and it did not affect the general change iterations. As the number of vertical cuts increase so did the number of printed parts that could be reused between iterations, and therefore the reusability of the prototype increased too. As the number of parts increased, their respective sizes (volume/area) decreased. This lead to the extent of the local changes being limited by the part boundaries. Resulting in less of the prototype having to be reprinted between iterations. This finding feeds into the Granularity and Shell decomposition strategies identified in Table 7.1 and Figure 7.1.

These results show that the base reusability arises from the LEGO internal structure, with increases occurring when printed parts can be reused. Consequently, the LEGO structure of a Hybrid Prototype is less sensitive to geometric changes that require parts to be reprinted. While the reuse (and therefore decrease in fabrication time) In both cases, any significant changes to the form (i.e. scaling or dimensional changes) will limit the effectiveness of a Reuse Focussed Hybrid Prototyping approach.

Table 7.7 The key findings from investigating Reuse Focussed HP

Finding	Description
Types of Change	For large, general changes reuse HP has little benefit (−2 % in fabrication time over normal HP, no change in reusability). There is significant benefit when the changes are local and small scale (−43 % in fabrication time, 16.43 % increase in reusability).
Number of Vertical Cuts	Increasing the number of printed parts increases the reusability of prototype iterations with local changes. However this does not affect general changes.

7.4 Concluding Remarks

This chapter has answered Research Question 3 through establishing different strategies for maximising the improvements Hybrid Prototyping brings to physical prototyping. Three of these strategies were investigated in the three case study objects - characterising the findings and how they apply to LEGO and 3D printed Hybrid Prototypes. The three strategies applied in the HP tool and investigated were:

- Adapting the fidelity through preservation of regions of interest.
- Parallelising the printing through distributing the print times across multiple printers.
- Improving the reusability between iterations through the management of Brixellating and Shelling algorithms.

In all cases, the results were compared against the simulation results (see Chapter 5) and the implementation results (see Chapter 6) to show how the benefits of HP can be improved. For example, the fidelity of a prototype needs to be reduced to 41 % to exceed the results found in simulation study reported in Chapter 5. Similarly, at least 3 printers are required to meet the 45 % reduction in fabrication time found in the simulation study.

Although all three strategies have been studied individually, they are not mutually exclusive and could be combined and applied simultaneously to a Hybrid Prototype instance. However, there are some decisions that the designer must consider around whether the priority and focus of the prototype is on fabrication speed, reusability, or fidelity. All three of these factors are impacted (both positively and negatively) by the strategies described and investigated in this chapter. The overall Hybrid Prototyping methodology and designer's workflow within the tool are described in Chapter 8, including the trade offs and decisions the designer needs to make.

Chapter 8

Hybrid Prototyping Methodology

8.1 Overview

Chapters 5 to 7 investigated the benefits and implementation of Hybrid Prototyping and answered the three research questions set out in this thesis. This chapter ties the work of the preceding chapters together to demonstrate the overall Hybrid Prototyping methodology as applied to a real world product. In doing so this addresses the overall aim of the research and overall contribution to knowledge.

The chapter starts with a description of the overall Hybrid Prototyping Methodology and its application in this thesis. This continues to show its implementation and how to use the tool and the user interface, before detailing a typical user workflow. The workflow takes the prototype from a digital model to physical Hybrid Prototype – it does not consider the design or creation of the prototype's geometry. It also shows the aspects of the HP methodology where the designer has to make key decisions about the purpose and requirements of the resulting prototypes.

Following this, the Hybrid Prototyping Methodology is applied to a series of prototypes used to develop an automatic light fitting. The results are compared against the original prototypes and discussed – highlighting the strengths and limitations of HP as applied in this scenario.

8.2 Hybrid Prototyping Methodology

The Hybrid Prototyping Methodology is the process of design decisions and considerations that afford the creation of Hybrid Prototypes through the combination of two different prototyping techniques. Figure 8.1 shows a high–level diagram of the overall Hybrid Prototyping Methodology.

The first consideration is the *type of product* being prototyped and the purpose of the prototype. This dictates the types of tools and techniques that can be used to realise useful HPs. From this, the *techniques to couple* need to be chosen from existing techniques (e.g. cardboard modelling) and new prototyping paradigms (e.g. augmented reality). Next the appropriate *prototype scale* should be chosen. This considers the size of the design (i.e. one–to-one scale or reduced scale prototype required) and the scale of the techniques (i.e. size of components or tooling) so that a reasonable and appropriate combination can be achieved. The *capabilities* of the chosen techniques determine the limits on resolution (i.e. precision of technique), fabrication time (i.e. capacity to fabricate parts), and costs (i.e. materials used). They also dictate how the two different techniques can be interfaced together. The *interfacing* is a critical part of HP as, at a fundamental level, it determines the feasibility of creating HPs with the chosen techniques.

The next decision is the prototyping *objective* – i.e. what is the driver for creating HPs? The three objectives identified (and investigated in this thesis) are to reduce fabrication time, reduce the material costs, and deciding the level of functionality of the prototype. These,

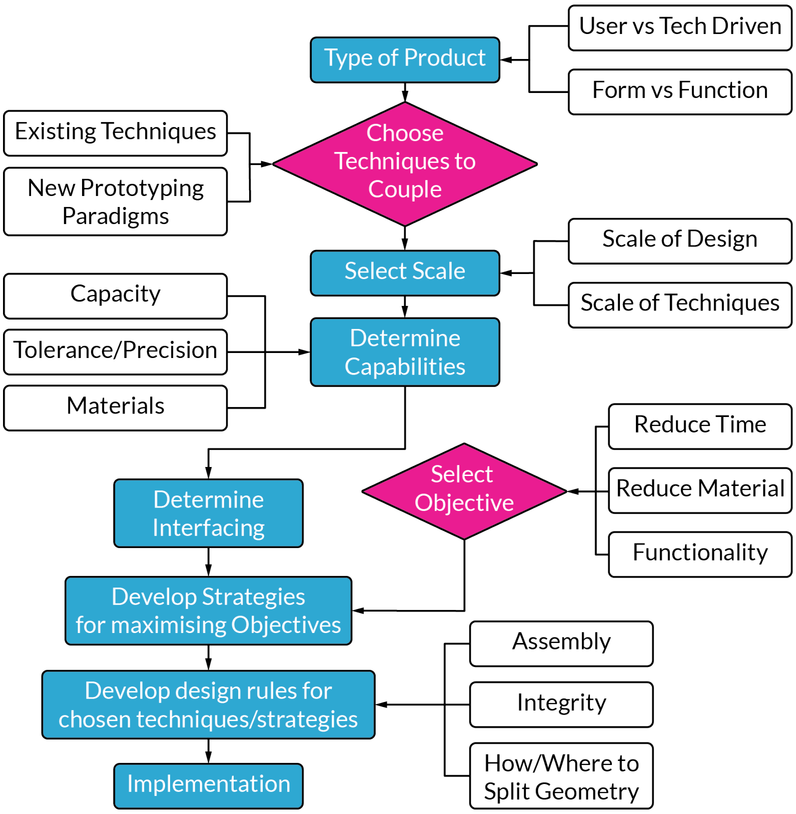


Figure 8.1 A high–level diagram of the overall Hybrid Prototyping methodology

combined with the *interfacing*, are then developed into *strategies* for implementing and maximising the chosen *objective*. The next step of the methodology is the creation of a set of *design rules* that describe how the *strategies* can be implemented as HPs. The *design rules* must consider the *assembly* and *integrity* when deciding how and where to *split the geometry* between the two techniques. The final part of the methodology is the *implementation* of the design rules as a tool for the designers to use.

This thesis has developed and characterised an instantiation of the Hybrid Prototyping methodology through the use of LEGO and 3D printing. Figure 8.2 shows how the overall HP methodology from Figure 8.1 has been applied in this thesis.

The LEGO and 3D printing HP methodology focused on form–based, user–driven products. The objects chosen from this *product type* were the computer mouse, video game controller, and digital camera (see Section 4.4.1). The justification for choosing LEGO and 3D printing as the *techniques to couple* was discussed in Section 3.3.2. Section 5.3 investigate the effect of brick–to–object ratio. This determined that for the size of objects, the best *scale* of brick was the commercially available LEGO brick. The *capabilities* of FDM printing and the library of LEGO bricks were described in Section 4.5.2. The tolerances of FDM printing that the *interface* between the LEGO bricks and the printed parts required redesigning. The redesigned interface was shown in Figure 6.20. Section 7.2 establishes three *strategies* to meet the two objectives – of reducing fabrication time and material costs – identified in Section 2.5. The *strategies* are Adapted Fidelity, Distributed Fabrication, and Reuse Focussed. These are then codified into the Design for Fabrication and

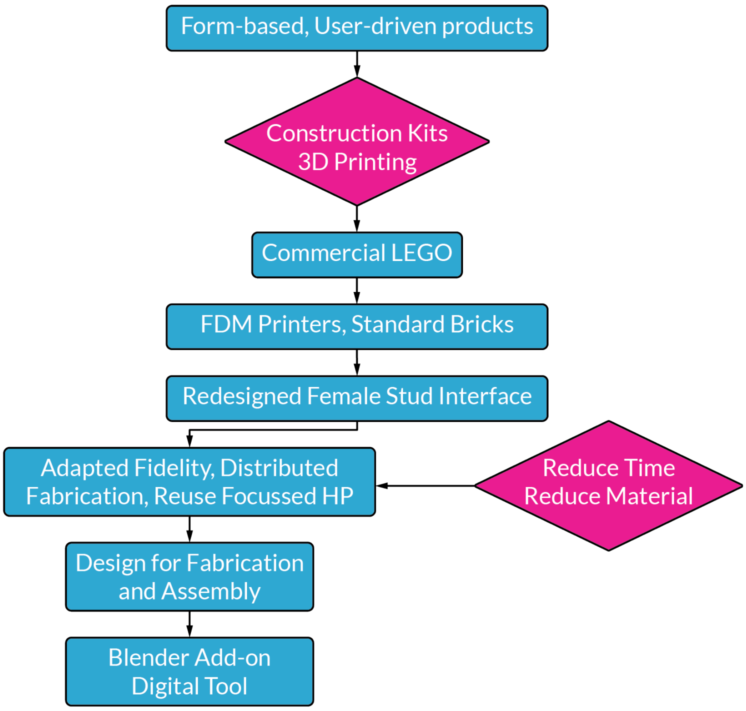


Figure 8.2 The Hybrid Prototyping methodology as applied in this thesis

Assembly (DfFA) rules in Section 6.3, to ensure that the prototypes can be fabricated, assembled, and maintain their integrity.

The final aspect of the applied HP methodology is its *implementation* in the digital tool. Much of the tool's algorithmic approaches and designer inputs have been described in earlier chapters, so Section 8.2.1 considers the tool's user interface and how the designer interacts and works with the tool to create their desired prototypes. The full process of using the tool can be seen in Figure 8.9.

Section 8.2.3 describes the different strategies required to achieve different goals designers may have within the Hybrid Prototyping methodology – i.e. their intent. These goals could include creating prototypes as fast as possible, or to make them as reusable as possible. The characterisation of Hybrid Prototyping in previous chapters will be drawn upon to show how this tool can help designers achieve these goals.

8.2.1 Digital Tool

The digital tool was created as an add-on for Blender 2.79 to leverage the Python based API to manipulate 3D geometry. This also permitted the creation of a custom user interface panel for creating Hybrid Prototypes. Figure 8.3 shows the user interface in the Blender 3D workspace with a partially assembled Hybrid Prototype of a computer mouse in the viewport.

Throughout the tool workflow there are automated checks that analyse the size and dimensions of the prototype's geometry – implemented from the DfFA rules established in Chapter 6. These warn the user if Hybrid Prototyping is unsuitable for the prototype they have designed.

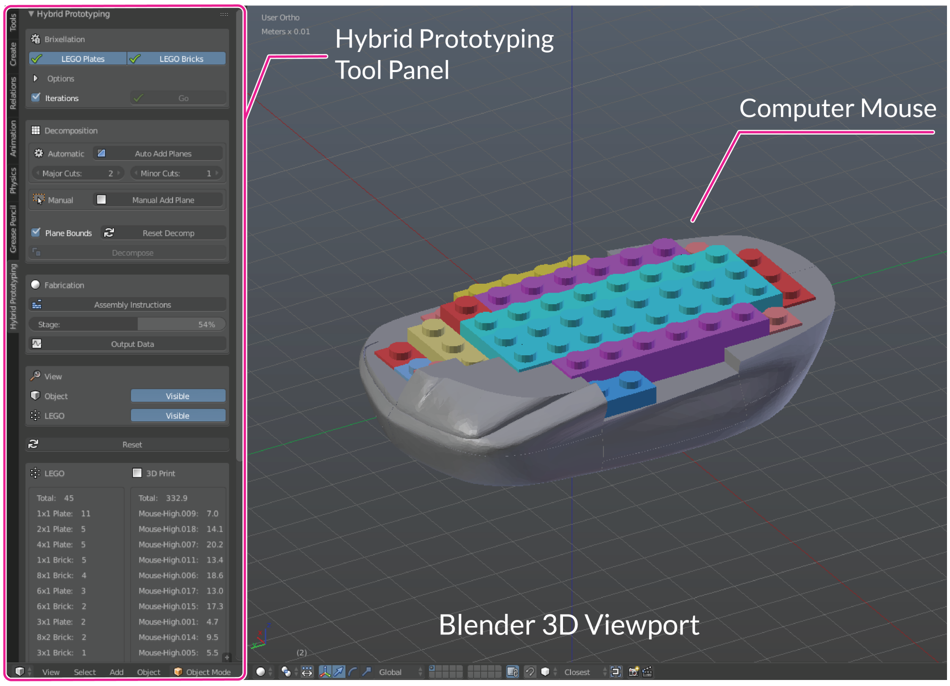


Figure 8.3 A screenshot of the custom Blender user interface for the digital Hybrid Prototyping tool

Figure 8.4 shows a detailed view of the tool panel with descriptions of each of the functions. It is segmented into groups of different functionality to make it easier for the designer to understand the stage of the tool they next require. These sections are (from the top of the panel down):

- Brixellation
- Decomposition
- Fabrication & Assembly
- View & Reset
- Performance Data

The following sections give a brief overview of the panel sections.

Brixellation

This section of the tool panel controls the implementation of the *Brixellation*, *Packing*, and *Shelling* algorithms (see Sections 5.2.1 to 5.2.3 respectively). The three algorithms are performed sequentially on the target geometry when the 'Go' button is clicked. The user can choose the types of LEGO bricks that are used in the Hybrid Prototypes – at a high level this is between 'Plates' and 'Bricks'. However, this can be expanded (when the 'Options' button is clicked) to include a more granular choice of available bricks. Figure 8.5 shows a screenshot of the expanded brick selection with different brick sizes selected.

There is an 'Iterations' toggle that informs the tool that there will be subsequent iter-

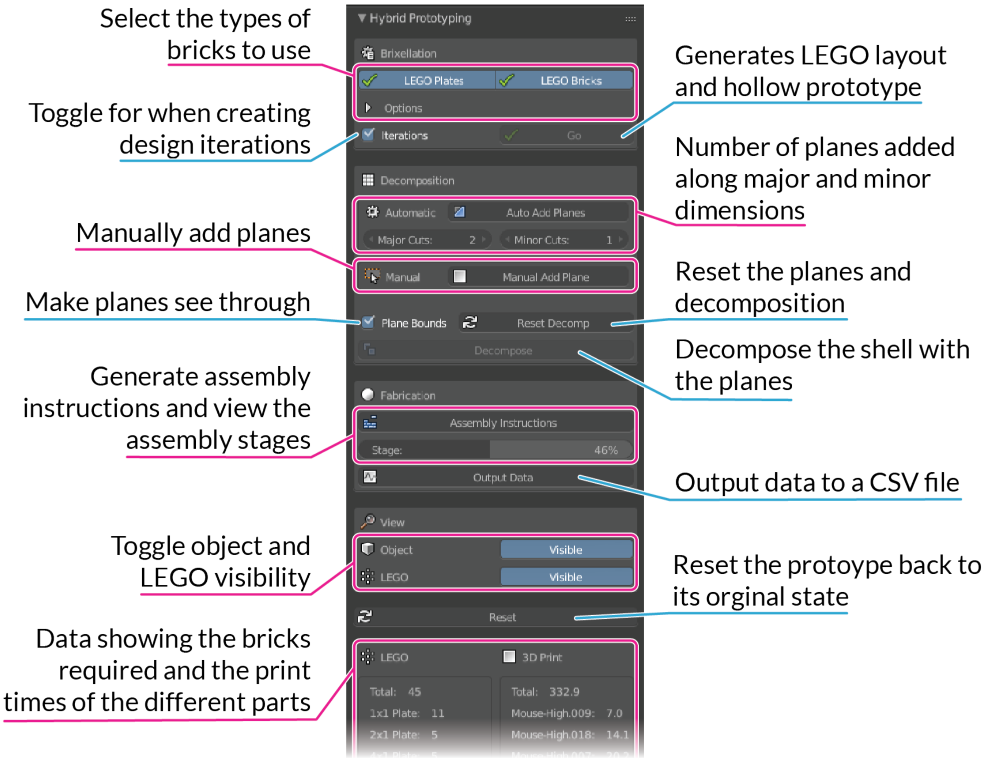


Figure 8.4 A detailed screenshot of the tool panel with descriptions of the different buttons and settings

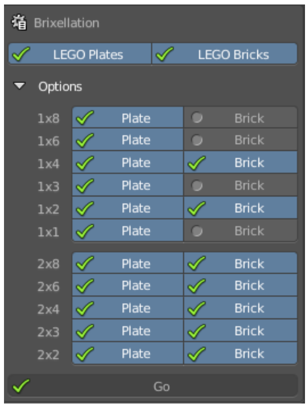


Figure 8.5 A screenshot showing the expanded brick selection

ations of Hybrid Prototypes. This is the implementation of the pilot tools outlined in Section 7.3.3.

Decomposition

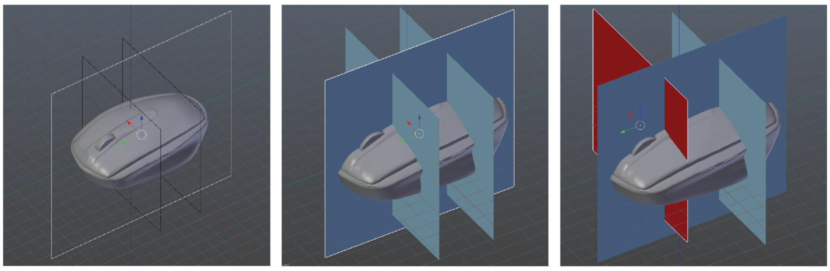
This section of the tool panel controls the decomposition of the hollow geometry so that it can be printed and assembled. If no planes are added, then the *decomposition* algorithm uses orthogonal planes within the LEGO structure to generate horizontal cuts (parallel to the ground plane) to decompose the geometry. However, it is possible to add planes to control where the geometry is decomposed. These can be added in two ways:

- Automatically – the number of planes along the major and minor dimensions are

chosen by the user. Based on these values the planes are added automatically in vertical positions.
- Manually – the user can add planes and move them into the desired position. This is important where it is desirable for specific features to be split or keep a feature whole.

These are not mutually exclusive, making it possible to add planes both ways to the same prototype. In both cases, the added planes are not fixed and can be translated, rotated, and scaled to required positions. To aid the user's positioning of the planes, a 'Plane Bounds' toggle switch changes the appearance of the planes from solid colours to just show their bounding box – allowing the user to see all the geometry of the prototype. This is shown in Figure 8.6a.

To ensure that only valid positions are used in the decomposition, tests are run to check that the planes are fully intersecting with the geometry. These feedback into the user interface and colour unacceptable planes red until they are made to be acceptable. This is demonstrated in Figures 8.6b and 8.6c. The 'Decompose' button is greyed out if there are any invalid planes, guaranteeing that the user does not create invalid geometry.



(a) Plane bounds (b) Acceptable cut locations (c) An unacceptable cut location

Figure 8.6 Screenshots showing the tool feedback in the UI when adjusting the decomposition cuts

There is also a button to reset the decomposition in this section. This resets the split geometry to one hollow part (i.e. post *Brixellation* and *Shelling*) and removes the decomposition planes. It allows the user to quickly explore different decompositions without having to rerun the previous algorithms.

Fabrication & Assembly

This section of the tool panel produces and shows the assembly instructions required to build the Hybrid Prototype, as well as outputting the data and printed parts. The 'Assembly Instructions' button generates the assembly order of the LEGO bricks and printed parts. This can then be viewed in the assembly order using the 'Stage' slider, similar to the manner in which FDM slicing software show 'Layer' views. Figure 8.7 shows four different stages from the assembly instructions for the computer mouse.

The 'Output' button creates a CSV file that includes the list of bricks and printed parts with estimated fabrication times. It also generates the STLs that need to be printed to

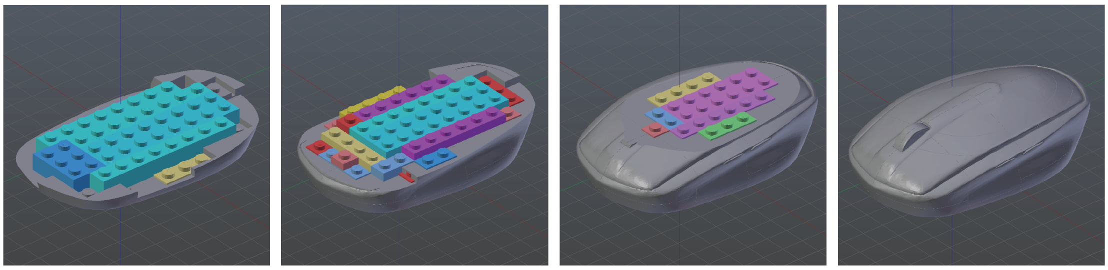
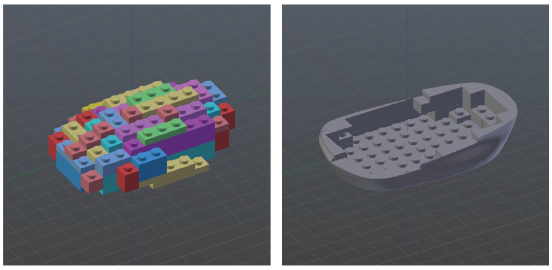


Figure 8.7 Screenshots showing the different stages of the assembly instructions for the computer mouse

create the Hybrid Prototype.

View & Reset

This section of the tool panel provides convenience functions for the user and is not required for the underlying Hybrid Prototyping tool. The two buttons toggle the visibility of the LEGO and printed parts respectively. This allows the user to quickly hide (or show) the different parts of the Hybrid Prototype. Figure 8.8 shows the functionality of these buttons.



(a) Only LEGO visible (b) Only printed parts visible

Figure 8.8 Screenshots showing the visibility of different parts of a Hybrid Prototype

Within this section of controls is the 'Reset' button. This is a global reset that returns the Hybrid Prototype back to the original 3D geometry of the design – undoing the decomposition, shelling and brixellation, removing the LEGO bricks, and any other parts. It can be used to quickly start the Hybrid Prototyping process again or to import different geometry.

Performance Data

Similar to the View & Reset section of the tool panel, this section does not impact the Hybrid Prototyping tool. Instead, it shows information about the current Hybrid Prototype. This includes the total brick count and breakdown of individual brick sizes required. The total print time is shown, as well as the individual print times for each part. The inclusion of this information allows the designer to quickly see the bill of materials and estimated print times – helping the designer make an informed decision about the state of the Hybrid Prototype instance.

8.2.2 Designer Workflow

Having now described the features of the digital Hybrid Prototyping tool, this section describes the workflow to create HPs with the tool. Figure 8.9 shows a flow diagram of this workflow.

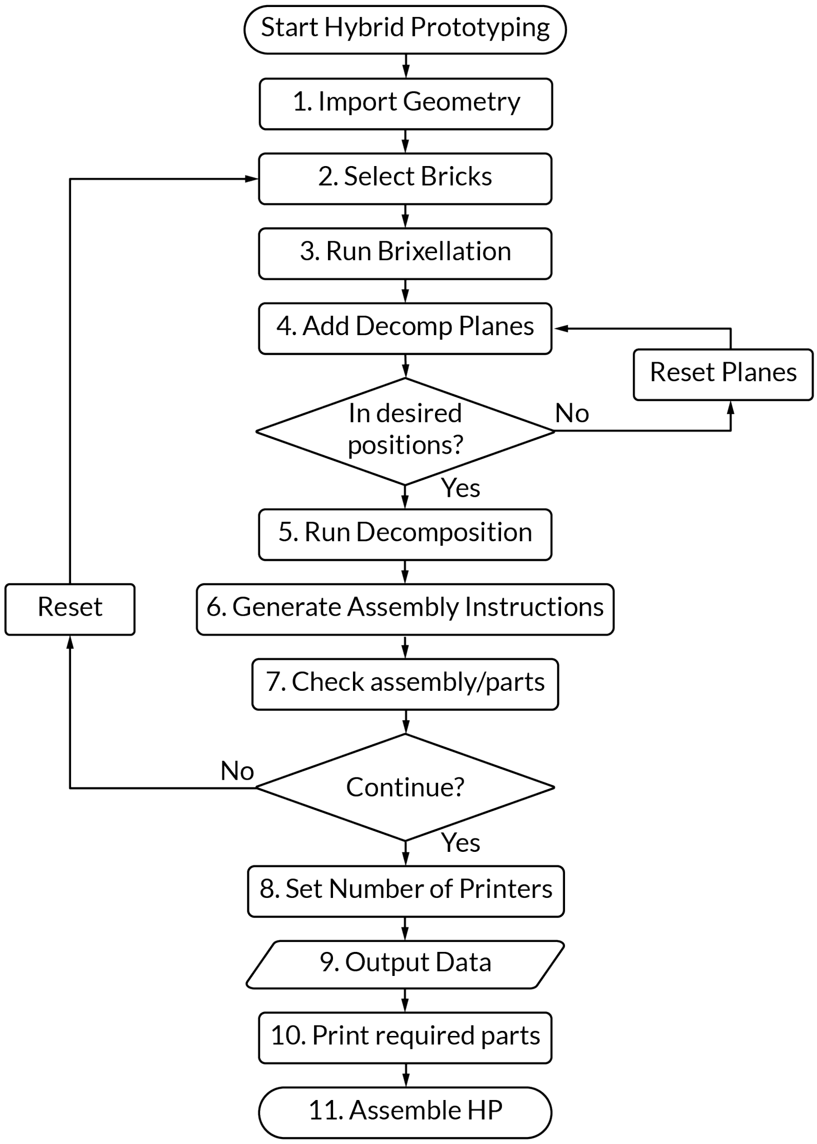


Figure 8.9 A flow diagram of the user workflow when creating Hybrid Prototypes

The workflow can be broken down into the following stages:

1. *Import geometry* – import the 3D geometry of the prototype as an STL file.
2. *Select bricks* – choose the types and sizes of the bricks to use in the Brixellation.
3. *Run Brixellation* – Click the button to *Brixellate*, *Pack* and *Shell* the prototype geometry.
4. *Add decomposition planes* – Automatically or manually add the decomposition planes. The planes can be positioned to desired locations and rotations.
5. *Run Decomposition* – Decompose the geometry into assemblable and printable parts.
6. *Generate assembly instructions* – Click the button to generate the assembly instructions.

7. *Check assembly/parts* – The slider can be used to verify the parts and assembly of the HP.
8. *Select the number of printers* – Set the number of available printers to use for the HP.
9. *Output data* – output the bill of materials and STLs of the geometry to be printed. This data also includes the list of bricks and the print queue for each printer.
10. *Print required parts* – Slice and queue up the parts to be printed.
11. *Assemble Hybrid Prototype* – assemble the Hybrid Prototype with the printed parts and required bricks using the assembly instructions.

As shown in Figure 8.9, there are several decision points where the designer must consider whether to continue with the process or to go back and change variables. The considerations when choosing the variables required for particular goals are described in Section 8.2.3.

The first decision is made at the point of decomposing the hollow geometry. The designer must choose to make the cuts with the positioned planes or to reset. The decomposition process in the tool cannot be altered later without reverting all the geometry back to its original state.

The second decision is required when outputting the Hybrid Prototype data (Bill of Materials, Part STLs for printing, Assembly instructions). Similarly, at this point modifications cannot be made once the data has been outputted – so the designer must confirm that the output is as desired.

8.2.3 Satisfying Designer Goals

Throughout this thesis, the research has focussed on two aspects of improving physical prototyping:

- Reducing a prototype's fabrication time.
- Reducing the material costs of fabricating a prototype.

These can be viewed as goals for designers when prototyping – can a prototype be created that provides sufficient information to answer the design question while also meeting these goals. As a result, the Hybrid Prototyping methodology can be used to provide improvements in these areas. The following sections take these two aspects in turn and consider how the HP methodology would be applied to meet each goal. However, it is worth noting that in practice the goals are not mutually exclusive. While they are addressed in turn here, they will both need to be considered and a trade-off sought.

Reduce Fabrication Time

As shown in previous chapters, the majority of the fabrication time of Hybrid Prototypes comes from the time taken to print the parts, rather than assemble the prototype. Therefore in order to reduce the fabrication time the focus must be to reduce the number and volume of parts that need to be printed or to consider ways to print the parts more quickly.

Figure 8.10 shows the decision tree for reducing the fabrication time of Hybrid Prototypes (against printing the prototype as single part). These decisions do not take into consideration the material usage, or the need for future iterations of a design.

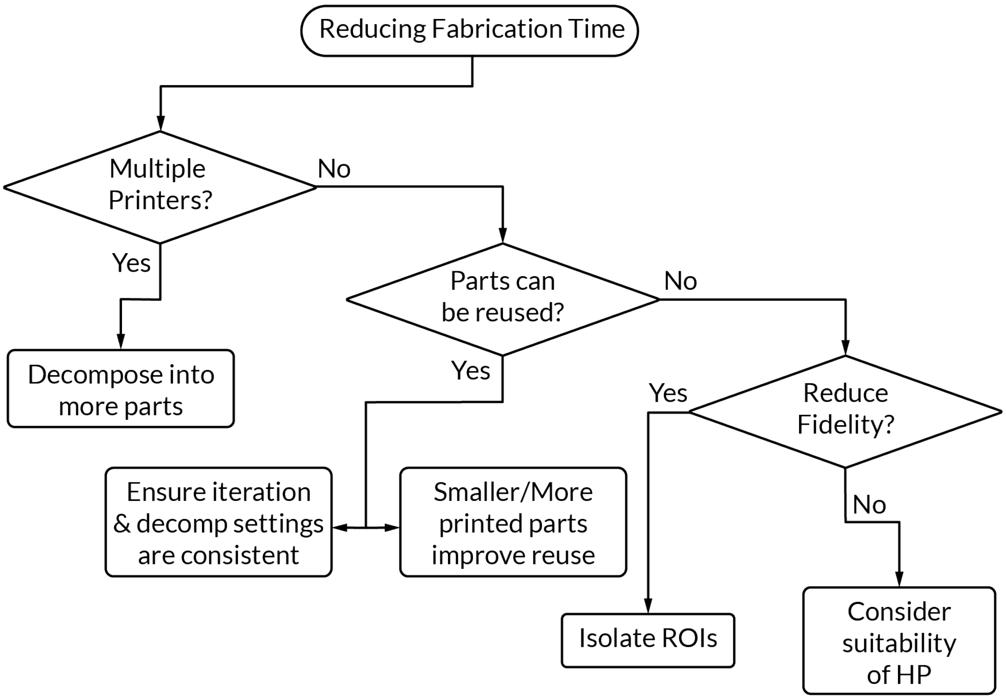


Figure 8.10 A decision tree showing the strategies to reduce the prototype fabrication time

The first factor is the availability of multiple printers. As shown in Section 7.3.2, distributing the printed parts over multiple printers results in significant reductions in fabrication time. Table 8.1 shows the reduction for different numbers of printers.

Table 8.1 The median difference in fabrication time between HP and a single print for different numbers of printers

Printers	Difference / %
2	−26.3
5	−64.7
10	−76.5

In order to leverage the benefits of multiple printers, the prototype must be split into enough parts to distribute over the printers. Consequently, when using the tool it is important to ensure the shell is decomposed into more parts – i.e. more planes are added and positioned during the *decomposition* stage of the tool workflow.

The second factor is whether parts printed and used in previous iterations can be used in the current iteration. Obviously, this only applies when there are prior iterations in the design process. Section 7.3.3 demonstrated that improvements in fabrication time could be achieved when parts from previous iterations could be reused. However, the improvements were dependent on the size and scope of the geometry changes between iterations. The mean difference in fabrication time between a single instance of normal HP and a reuse focussed HP are shown in Table 8.2.

Table 8.2 The mean difference in fabrication time between normal HP and reuse focussed HP

Change	Difference / %
General	−2.0
Local	−43.4

As a result, the designer must consider the degree of change between iterations if they want to minimise fabrication time. With smaller, more localised changes permitting a greater proportion of reuse from one iteration to the next, and consequently faster overall fabrication time.

The third factor is the level of fidelity required from the prototype. In Section 7.3.1, the fabrication time could be improved through lowering the fidelity of the HP. This reduced the number and volume of parts that needed printing by isolating regions of interest – i.e. areas of the design the designer was focussed on. Table 8.3 shows the effect of changing the fidelity on the difference in fabrication time between printing as single part and using HP. Consequently, the designer must balance the required fidelity level with the goal of reducing fabrication time, and decide the location and size of the regions of interest.

Table 8.3 The difference in fabrication time between HP and a single print for different levels of fidelity

Fidelity / %	Difference / %
80	1.5
60	−22.5
40	−46.5
20	−70.6

If none of the three factors can be used to help reduce the fabrication time, then the suitability of using Hybrid Prototyping to reduce fabrication times must be considered. As discussed in Chapter 6, in some cases, smaller objects may take longer to produce with HP than printing as a single part. In the case study objects, only the largest (the digital camera) was fabricated quicker using HP. Consequently, the designer must decide if the other benefits of HP (see Section 8.2.3) are desirable and hence whether it is worth using HP as the prototyping technique.

While the decisions shown are followed in a linear fashion, in practice all factors could be combined in some situations. For example, if there was an isolated region of interest of the design that had been previously iterated – some of the previous parts could be reused. Then the parts that needed printing (i.e. only the non-reused parts and those in the region of interest requiring printing) could be split over multiple printers. This would allow designers to quickly explore and learn about the designs through minimising the fabrication time to enact the changes.

Reduce Material Cost

In this thesis, the reusability metric has been used as a proxy for the amount of material saved – i.e. a reusability of 50 % means that half the prototype can be reused, and therefore not printed, saving 50 % of the material costs. Chapter 6 considered the reusability of a prototype to be proportion of the volume occupied by LEGO. This was extended in Chapter 7 to include the volume of the printed parts that could be reused between iterations. As a result, there are several factors that affect the reusability, and therefore material cost, of a Hybrid Prototype. Figure 8.11 shows the decision tree for reducing the material usage when Hybrid Prototyping.

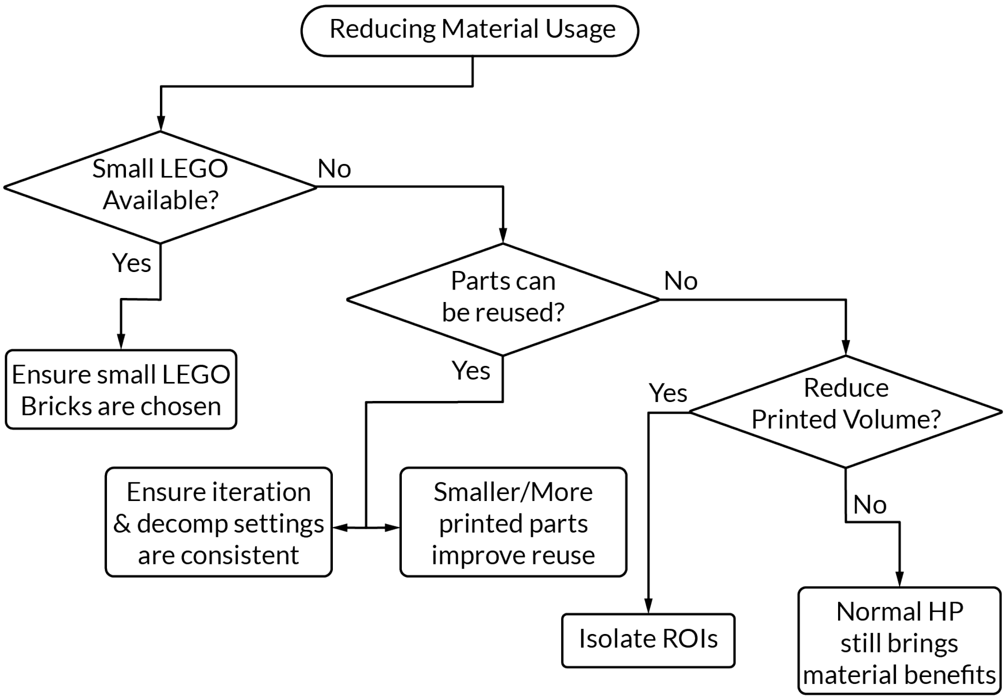


Figure 8.11 A decision tree showing the strategies to reduce the prototype material usage

The first factor in reducing the material costs and improving the reusability of a HP is the size and quantity of available LEGO bricks. Chapter 5 investigated the effect of different brick sizes (from different construction kits) and found that as the bricks got smaller, the reusability increased. However, as this implementation of HP is limited to standard LEGO bricks, only bricks from this library can be considered. In order to increase the reusability, the designer must consider using smaller bricks (i.e. 1×1 plates, see Figure 8.5). Larger bricks can also be used as their usage is calculated by the *packing* algorithm. Their inclusion reduces the overall number of bricks required – but does not affect the reusability when combined with smaller bricks. Table 8.4 summarises the findings from Chapter 6 showing how the difference in reusability between using plates and bricks decreases as the prototyped object gets larger.

Consequently, the designer should consider the relationship between the size of the object and use of different sized LEGO bricks.

The second factor, similar to Section 8.2.3, is the availability of parts to be reused from

Table 8.4 The mean difference in reusability between using 1×1 plates and 1×1 bricks for the three case study objects

Object	Difference / %
Computer Mouse	25.0
Video Game Controller	15.2
Digital Camera	5.2

previous iterations. Chapter 7 found that by reusing parts between iterations the reusability could be increased in some situations. This effect was most pronounced when performing small, localised changes between iterations – i.e. the more two iterations have in common the greater the reusability between iterations. Table 8.5 shows the findings. The increase of 16.4 % arises from the additional reusability of printed parts between iterations.

Table 8.5 The mean difference in reusability between normal HP and reuse focussed HP

Change	Difference / %
General	0.0
Local	16.4

In order to increase the reusability between iterations, the designer must consider two things:

- Small changes between iterations result in a more reusable prototype.
- Smaller (and therefore, more) printed parts reduces the volume of parts requiring reprinting between iterations and correspondingly increases reusability.

The designer must ensure that there are sufficient numbers of planes to decompose the hollow shell (more/smaller parts) and attempt to adjust small areas of the design between iterations.

The third factor takes the approach of reducing the volume of the prototype that is non-reusable. This is achieved through removing the printed parts not within particular regions of interest, instead focussing on printing only the parts necessary for the designer to gain the relevant information. The result is a prototype that is more reusable as it is predominantly constructed out of LEGO with the trade-off of reducing the fidelity in the areas not specified as being ROIs. In this case, the lower the fidelity the greater the reusability – with a 0 % fidelity prototype being 100 % reusable as it is only constructed from LEGO.

If none of the decision factors (shown in Figure 8.11) can be applied to increase the reusability and decrease the material cost, then using Hybrid Prototyping over printing the prototype still achieves benefits in reusability and material usage.

In the same manner as Section 8.2.3, situations could arise where all three strategies could be applied. This could compound the results and result in high reusability between iterations.

8.3 Case Study

The overall Hybrid Prototyping methodology is demonstrated in the prototypes from a real-world product development process for a retro-fitted automatic light bulb, "See Sense". This product aimed to create affordable smart lighting that would react to the presence of a person or turn on at specified times. The designs included buttons and interfaces for the user to control how the light behaved; from adjusting motion sensitivity to setting timers. The prototyping process used foam models for early concept generation, before using 3D printed prototypes to elicit stakeholder feedback and improve the design. This provides a real-world validation case for Hybrid Prototyping.

The foam prototypes can be seen in Figure 8.12a, and the 3D printed ones in Figure 8.12b (note: the printed prototypes are missing the light fitting). These prototypes are approximately 65 mm wide and 50 mm tall. For this case study investigation, only the 3D printed prototypes are considered as they show how the design progresses at each prototype instance.

(a) The three foam prototypes of concept ideas

(b) The progression of the four 3D printed prototypes

Figure 8.12 The foam and 3D printed prototypes of the See Sense automatic light fitting

8.3.1 Method

As the digital files of the prototypes did not exist, the 3D models were generated in Blender from dimensions and reference images of the prototypes. This ensured that HP could be used on these prototypes, and that print settings could be controlled and predicted timings generated. Figure 8.13 shows the digital versions of the four prototype iterations. A standard light bulb screw thread (E27) was added to each digital model as it was missing from the physical prototypes.

This demonstration of the Hybrid Prototyping methodology focusses on reducing the fabrication time of the prototype iterations by employing the different strategies identified in Chapter 7. While the reusability will be reported, it will not be the driving factor in the method of investigation. The method will investigate and compare four different strategies to fabricate the prototypes:

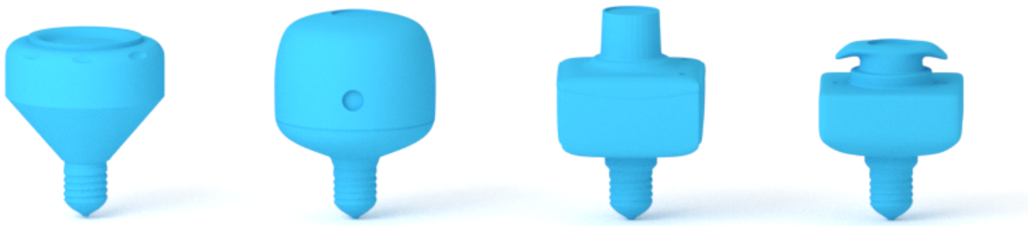


Figure 8.13 The digital 3D models of the four prototype iterations

- Printing as a single part – this will act as a baseline for comparing the other three strategies.
- Distributed fabrication (DF) HP – normal HP approach but distributing the printing over four printers.
- Adapted fidelity (AF) HP – Selectively printing only the regions of interest combined with the LEGO structure. The focus of the prototypes was on the user interaction, as a result the upper portions of the designs were selected as ROIs. Table 8.6 shows the level of fidelity (c.f. Section 7.3.1 and Equation 7.1) when using the chosen ROIs. Only one printer was used in this strategy.
- Reuse focussed (RF) HP – Managing the between iteration reusability to reduce additional fabrication required. The common aspects of the designs (i.e. the lightbulb screw thread) were preserved between iterations. Only one printer was used in this strategy.

In all four cases the fabrication time and reusability results will be reported for each individual iteration, and then as a cumulative total for the four prototyping iterations.

Table 8.6 The level of fidelity for the four iterations when using Adapted Fidelity HP

Iteration	Fidelity / %
1	53.9
2	56.7
3	62.2
4	58.1
Mean	57.7

8.3.2 Results

Figure 8.14 shows the per iteration fabrication time using the four different strategies. For every iteration, Distributed Fabrication (DF) and Adapted Fidelity (AF) are quicker than printing the prototype as a single part. However, the Reuse Focussed (RF) performed worse than a single printer in every case.

Figure 8.15 shows the cumulative fabrication times after each iteration for the four

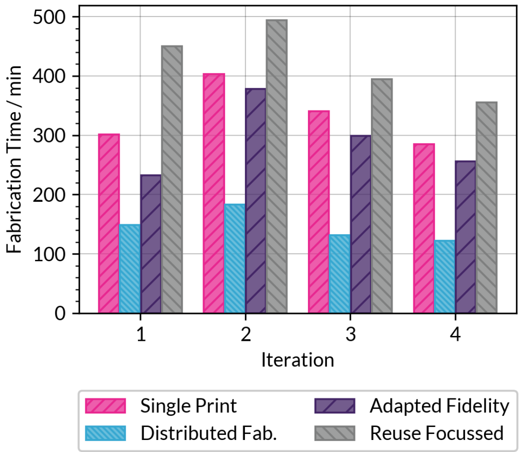


Figure 8.14 The fabrication times for each iteration for the four strategies investigated

strategies. Based on Figure 8.14, the results are not surprising, with DF and AF having shorter overall fabrication times, and RF taking longer than printing each iteration as a single part.

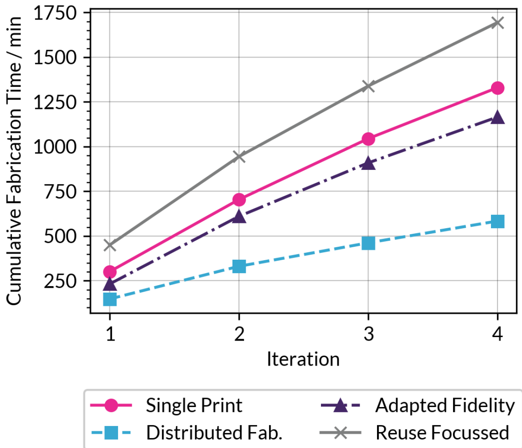


Figure 8.15 The cumulative fabrication time after each iteration for the four strategies investigated

Table 8.7 summarise the results, showing the mean iteration fabrication time, the total cumulative fabrication time, and the percentage difference between the three HP strategies and printing as single parts. The percentage difference highlights how the different HP strategies can impact the fabrication times of prototypes. In this case, the best is the DF (with four printers) giving a −56.1 % reduction in fabrication time, followed by AF at −12.4 %. The worst was RF which actually increased the fabrication time by 27.4 %.

Table 8.8 shows the level of reusability for the four strategies for each iteration. Obviously, the single prints have no reusability. The DF and AF have the same reusability as only the LEGO is considered reusable as there is no attempt to match printed parts across iterations. Here, RF performs slightly better – giving rise to an approximately 2 percentage point increase in reusability (Iteration 4 is the same as there is not a fifth

Table 8.7 The mean iteration and cumulative fabrication times for the four strategies investigated. The difference from printing is also included

Strategy	Mean / min	Cumulative / min	Difference/ %
Single Print	332.42	1329.66	–
DF	145.97	583.86	−56.1
AF	291.30	1165.18	−12.4
RF	423.43	1693.73	27.4

iteration to match parts against).

Table 8.8 The level of reusability for the iterations for the four strategies investigated

Strategy	Iter. 1 / %	Iter. 2 / %	Iter. 3 / %	Iter. 4 / %
Single Print	0.0	0.0	0.00	0.0
DF	56.1	62.8	60.4	56.4
AF	56.1	62.8	60.4	56.4
RF	58.9	64.7	62.9	56.4

Figure 8.16 shows the cumulative printer material usage after each iteration for the four strategies. This shows that there is a significant reduction in material usage when using HP over single prints. AF performed the best, requiring less than a quarter of the printed material than printing the iterations as single parts. It also shows that, in this scenario, RF provides a small reduction in material usage over DF.

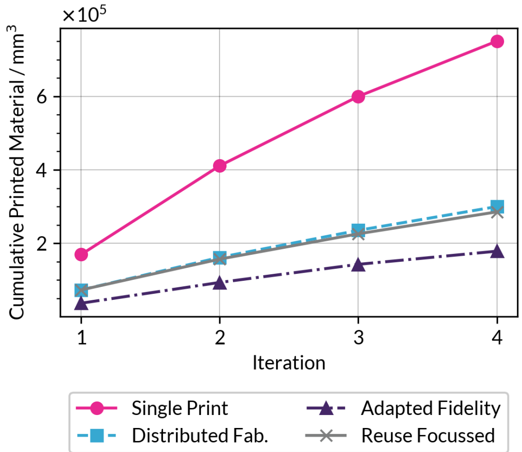


Figure 8.16 The cumulative printed material usage after each iteration for the four strategies investigated

Table 8.9 summaries the results; showing the mean iteration and cumulative material usage, and the percentage difference from single print iterations. This confirms the performance of AF with a reduction in material use of −76.2 %. The slight improvement of RF over DF (2 percentage points) arises from not having to reprint parts of the design (i.e. screw lightbulb fitting).

Table 8.9 The mean iteration and cumulative material usage for the four strategies investigated. The difference from printing is also included

Strategy	Mean / mm^3	Cumulative / mm^3	Difference/ %
Single Print	1.88×10^5	7.51×10^5	–
DF	7.50×10^4	3.00×10^5	−60.0
AF	4.46×10^4	1.78×10^5	−76.2
RF	7.14×10^4	2.86×10^5	−62.0

8.3.3 Discussion

There are several interesting points to draw out from applying different strategies to Hybrid Prototyping to a series of real-world prototypes. The strategies were implemented such that there was little overlap and that their key traits could be investigated independently. As mentioned in Section 8.2.3, in practice the application of HP would involved a combination of these strategies depending on the situation and the designer intent.

The first observation is the poor performance of the RF. Section 7.3.3, showed that the improvements in fabrication time from this strategy were dependent on the scale and scope of changes between iterations. The findings showed that the greatest potential in using RF were in situations where there were small, localised changes between iterations. It follows that it is only worth doing if the designer creates variants or similar products and then can use the parts across projects. Here, in the See Sense prototypes, there are large geometric changes to overall size and form – with the only constant part being the screw lightbulb fitting. Consequently, the results of RF were to be expected and the strategy tends towards performing normal HP with a single printer. However, this strategy did lead to a slight increase in reusability – arising from the screw lightbulb fitting remaining constant between iterations. This translated into a slight material saving over DF over the course of the four iterations.

The two strategies that performed better than printing the whole prototype, employed different strategies for reducing the 3D print requirements of the HP. The first, AF, reduced the amount of parts that need printing by only printing regions of Interest. In the See Sense prototypes, this was the upper section with which the user interacts and manipulates. The fidelity for each iteration was reduced to an average of 57.7 %, resulting in a 12.4 % reduction in fabrication times. This strategy also resulted in the greatest material saving over printing as a single part – requiring only a quarter of the material. To improve the reduction in fabrication times, the fidelity would have needed to be reduced further. However, the possibility of fidelity reduction becomes dependent on the prototype requirements and the focus and intent of the designer.

The second strategy, DF, spreads the 3D printing load over multiple printers – in this case, four. This permits the creation of 'full' fidelity prototypes, while achieving significant reductions in fabrication time. Section 7.3.2 showed that the improvements from distributing the printing were dependent on two factors; the number of printers, and the number of parts. While using more printers resulted in a greater reduction, there were diminishing returns – with the largest improvements arising from using 2–6 printers. Consequently, only four printers were used in this case study, showing that it was possible to halve the fabrication time when using Hybrid Prototyping. The DF strategy did have the smallest reduction in material usage at −60.0 %. However, all the HP strategies offered significant savings in material usage with an average reduction of 66.1 %.

This real-world case study was used to demonstrate the different strategies to HP, and so the optimum solution to minimise the fabrication time or material usage was not investigated. It is challenging to find a minimum as the decisions in the prototyping process are heavily dependent on the designer, audience, and the purpose of the prototypes. Furthermore, as discussed in Section 8.2.3, there could be other goals the designer has in mind that could focus on material use, reusability, and editability over minimising fabrication time.

8.4 Concluding Remarks

This chapter has described the overall Hybrid Prototyping methodology and how it was instantiated through the use of LEGO and 3D printing. The first half of the chapter started by documenting the digital tool and how to use the custom user interface in Blender, before outlining the designer workflow and how it fits into the prototyping process. A key part of the workflow is the ability to meet designer goals when prototyping (e.g. reducing fabrication time or material costs). The different strategies and decisions to meet these were explored with flow diagrams showing the key decision points.

The second half reported a demonstrative case study, using four iterations of a real-world prototype process for an automatic light fitting, See Sense. Through this case study, three different strategies to Hybrid Prototyping were compared against printing the iterations as single parts. This showed how the HP strategy taken affected the fabrication time and material usage of the prototypes. Distributed Fabrication HP proved to be the most effective by more than halving the cumulative fabrication time, followed by Adapted Fidelity HP providing a 12 % reduction. Reuse Focussed HP performed the worst, causing an increase in fabrication time. With regards to material usage, all the HP strategies offered significant reductions in material usage, using on average a third of the material compared to single prints. Adapting Fidelity HP achieved the greatest reduction of −76 % – quartering the amount of material required.

The results showed how it was important for the designer to make decisions about the strategy taken to ensure the desired outcome and goals when prototyping. These decisions must consider the purpose of the prototype, level of fidelity required, and the scope of the changes between iterations.

Chapter 9

Discussion

9.1 Overview

This chapter discusses the methodology and research reported in the preceding chapters of the thesis. The discussion is broken down into three areas:

- Fulfilment of the aim – has the research achieved what it set out to do?
- Generalisability – how can the research be applied beyond the scope of the thesis?
- Future work – what are the next steps for the research?

In the following section each of these is addressed; starting with the fulfilment of the aim that was initially set out in Chapter 4. For each of the research questions the suitability of the method and the key findings are discussed. Reflections on the research undertaken to answer the questions are also included.

The next area of discussion is the generalisability of the research. This takes each of the constraints applied to the scope of the research and considers how the research could be extended beyond the scope. These constraints were as follows: the types of products; the stage in the design process; and the functionality of the prototypes.

Following on from the generalisability, potential avenues for future work leading on from the thesis are posited. This future work should investigate how designers use HP in the design process and measure the impact on the products designed. Other efforts could include extending the digital tool to accommodate curved and sloped LEGO bricks and moving parts with LEGO Technic. Furthermore, there is scope to automate the tool decisions within Hybrid Prototyping, allowing designers to focus on prototyping what they need to.

9.2 Fulfilment of the Aim

The first area for discussion is whether the research aim was fulfilled by the research undertaken over the course of the thesis. As set out in Chapter 4, the thesis aim was as follows:

> "To investigate and characterise the coupling of LEGO and 3D printing to reduce prototype fabrication time and material use, while preserving appropriate fidelity."

This aim was met through the development and evaluation of a LEGO and 3D printing based instantiation of the Hybrid Prototyping methodology. A diagram of the overall HP methodology can be seen in Figure 8.1 and how it is applied in the thesis in Figure 8.2. This permitted designers to create high fidelity prototypes by using LEGO to occupy the volume of the prototype with printed parts attaching to it. This reduced the amount of printing required and therefore also reduced the overall fabrication time and material used to create the prototype in the case studies.

The LEGO and 3D printing HP methodology consisted of the following areas:

- Design for Fabrication and Assembly rules that ensured the viability and suitability of the hybrid prototypes.
- A software tool that generated the required geometry and list of bricks, as well as the instruction set. This included:
  - Algorithms for Brixellating, Packing, Shelling, and Decomposing the prototype geometry.
  - Geometry checks to ensure suitability of applying the HP methodology.
  - Generation of assembly instructions.
- Exploration of the trade-offs the designer must consider when using the tool.

However, establishing the methodology itself does not completely fulfil the research aim. In order to investigate and characterise the methodology, the aim was broken down into three research questions. These research questions were answered through iterative development and subsequent evaluation of the methodology in Chapters 5 to 7 respectively. These chapters addressed the following questions:

1. What are the potential time and material savings from Hybrid Prototyping?
2. How can Hybrid Prototyping be implemented in practice?
3. How can the time and material savings of Hybrid Prototyping be maximised?

Chapter 8 followed these chapters, tying all the Research Questions together through the demonstration and characterisation of the overall hybrid prototyping methodology in a series of real-world prototypes.

Table 9.1 The thesis objectives and how they relate to the research questions

No.	Objective	RQs
1	Establish & implement technology platform and method	1, 2, 3
2	Implement simulation experimentation	1
3	Characterise theoretical benefits	1
4	Establish requirements and method for practical implementation	2
5	Implement practical method	2
6	Establish strategies to maximise practical benefits	3
7	Investigate & characterise strategies for maximising benefits	3
8	Characterise & demonstrate benefits in case studies	1, 2, 3

Several objectives were set out to provide achievable goals to guide answering the research questions. Table 9.1 shows these objectives as introduced in Chapter 4. The completion of these objectives demonstrates the fulfilment of the overall research aim of this thesis.

Taking each of the research questions in turn, the following sections discuss the findings, and suitability and limitations of the method.

9.2.1 Research Question 1

The first research question was:

> "What are the potential time and material savings from Hybrid Prototyping?"

This question was answered by Objectives 1, 2 & 3 in Chapter 5. The first objective established the preliminary development of the algorithms required for creating LEGO and 3D printed prototypes. A simulation–based method allowed the algorithms and their output to be explored and characterised – meeting the second objective. For Objective 3, the simulations were used to investigate and characterise how the fabrication time and reusability were affected by different sizes of construction kit, and different objects at different sizes.

The results showed promising benefits to using HP, with a possible 45 % reduction in fabrication time and a reusability of 55 %. The key findings are summarised in Table 9.2.

Table 9.2 The key findings from Research Question 1

Finding	Description
Fabrication Time	The fabrication time initially decreased with decreasing brick size, however there was a threshold where smaller bricks led to longer fabrication times. The greatest reduction was −45 % over printing as a single part.
Reusability	The reusability tended to 100 % as the brick size decreased. At the minimum fabrication time, the reusability was 55 %
Brick Size	The simulations used a brick size normalised to the object size, expressed as a ratio. The optimum brick:object ratio was in the range of 1:2500 – 1:1250.

Method & Limitations

The simulation based method was a reasonable approach to take for two main reasons:

- The focus on fabrication time and material usage resulted in a deterministic problem – albeit one with a large number of different variables. Consequentially, no variance in the simulation output occurred from repetition, and each simulation needed to only be run once (i.e. there was no need to investigate variance which would be present with user studies or ones with stochastic elements).
- The initial prototype geometry was already in a digital file format (typically STL, commonly used in 3D printing). Therefore, using computer simulations to manipulate and perform experiments on the geometry avoided unnecessary conversions between physical and digital domains and allowed for rapid simulation runs.

A key part of the simulations was the estimation of the print times, assembly times, and subsequently, fabrication times. The print time and assembly time models (see Equations 5.11 and 5.12 respectively) allowed the fabrication times for different prototypes to be calculated within the simulations without having to import the geometry into 3D printing slicing software.

However, the largest issue with the simulations was that these estimation models were based on empirical data, and so the validity of the simulation results relied on the validity of the fabrication time estimations. The reliance on empirical data arose for two reasons:

- The variability and complexity of printer settings and part orientation results in a large variation in the speed, quality and strength of printed parts [102], making it challenging to isolate the effects of HP. Consequently, the print settings were fixed (at 0.15 mm layer height, 18 % infill, and 60 mm/s) and part orientation ignored to generate a volume based print rate (see Figure 5.8) that could be used in the simulations.
- There was no existing literature or documentation on the assembly rates of LEGO models – even from anecdotal sources. Therefore, data had to be collected on the assembly rates of LEGO models. This data was then used to calculate how long it would take to assemble a given number of bricks.

The use of these empirical models is considered to be valid as they were kept constant between simulations and allowed direct comparisons of fabrication time to be made between different shapes and their sizes. The print rate model could be improved by determining the actual print times of the resultant parts rather than relying on their volume. However, as Figure 5.8 shows the overall relationship between volume and print time is a strong linear fit, and accounting for the deviations from the line of fit would not significantly alter the results presented.

The brick assembly rate does not consider the brick size and the associated dexterity required to manipulate them. However, by using participants creating models with a small design task, a conservative estimate for the assembly rates was calculated as it included searching for bricks, considering their placement and assembling the model.

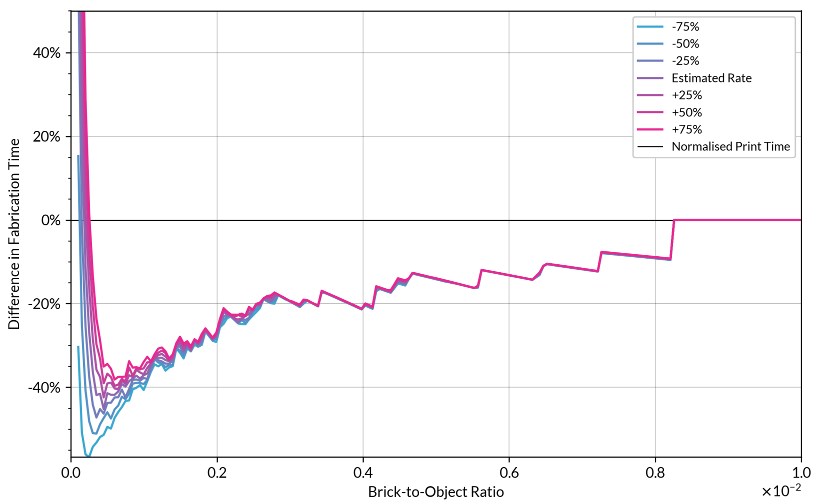


Figure 9.1 Sensitivity analysis of the LEGO brick assembly estimation rates. Only the medians are plotted for the different fabrication times

Figure 9.1 shows the sensitivity of the fabrication time to changes in the estimated assembly rates. It shows that there is little sensitivity to the LEGO assembly rate and that

[102] Goudswaard, M. et al. (2017) *Democratisation of design for functional objects manufactured by fused deposition modelling (FDM): lessons from the design of three everyday artefacts*

the fabrication time is dominated by print times. The assembly rate estimate could be further reduced with sorted bricks and detailed instructions, or even by performing the assembly with an automated pick-and-place machine. Consequentially, an improved estimate would likely reveal an increase in the potential benefits of using LEGO and 3D printing Hybrid Prototyping.

9.2.2 Research Question 2

The second research question was:

> "How can Hybrid Prototyping be implemented in practice?"

This was addressed by Objectives 4 & 5 in Chapter 6. For the fourth objective, existing literature on the design rules for FDM 3D printing and for constructing LEGO models were used to develop the Design for Fabrication and Assembly rules. By establishing the method and constraints for creating Hybrid Prototypes, HP could be fully implemented in the digital tool – building on the preliminary algorithms developed in RQ1. Further algorithms were developed, including the *Decomposition* algorithm (see Equation 6.1) which separates the hollow shell into printable parts, creating a prototype that can be assembled.

The implementation of HP was explored in three iterations of the three case study objects. The key findings are summarised in Table 9.3. However, this implementation of HP showed that the findings from RQ1 were idealised and could not be obtained with a single printer, and that further work was required to achieve them.

Table 9.3 The key findings from Research Question 2

Finding	Description
Implementation	It is possible to create printable and assemblable HP prototypes using the DfFA rules and digital tool.
Fabrication Time	Using a single printer, the HP fabrication times exceeded that of printing the prototypes as a single part (only the digital camera was quicker). The difference between using LEGO plates or bricks had little effect on the fabrication times.
Reusability	Using LEGO plates over bricks increases the reusability of the prototype, however this effect diminishes as the prototype gets larger.
Part Distribution	The distribution of part print times narrows as the number of parts increases – making it easier to distribute over multiple printers. It also shows a need to balance the print times when a prototype is decomposed into fewer parts.

Method & Limitations

As the sophistication increased throughout the development of the HP tool, the print time estimation model evolved to match. The updated print model considered the surface area (as well as the volume) when calculating the time estimate (see Equation 6.5). This ensured that the level of decomposition affected the print time. Similar to the original print model, this was also based on empirical data, so that the speeds for infill and wall volumes could be calculated. However, the main limitation with this approach is how the surface area is used to calculate the volume of the wall. This takes the surface area and multiplies it by a thickness. As Figure 9.2 shows, this can lead to overestimates in convex geometry, and underestimates in concave geometry, and therefore affect the print time estimates, particularly for intricate components.

However, as the same print model used was used across all case study experiments (for all print time estimations) it meant that comparisons made between results were valid. If a more accurate approach to calculate the volume of wall thickness is required, a Minkowski Sum of the 3D surface could be used [167], however the substantially increased computational overhead may outweigh the benefit of the increase in accuracy.

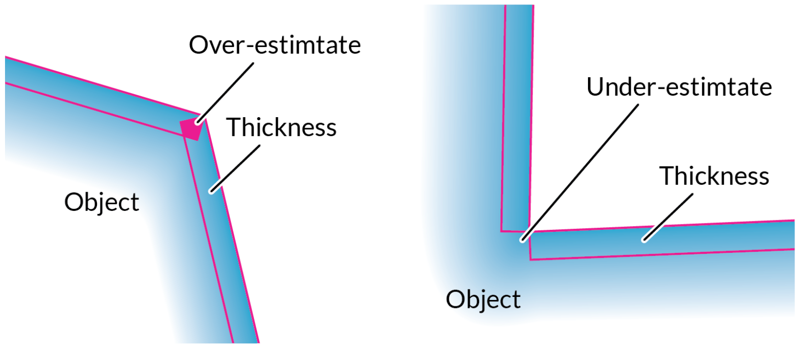


Figure 9.2 Diagrams showing how the surface area based calculation can lead to over or under estimates of the wall volume

The second limitation was the approach to the shell decomposition. While different types of boundary cuts (e.g. interlocking or curved) were considered, planar cuts were used to demonstrate the decomposition in Hybrid Prototyping. Furthermore, these were kept perpendicular (vertical cuts in the X-Z or Y-Z Planes) or parallel (horizontal cuts in the X-Y Plane) to the ground plane in order to simplify the calculations of their locations. For the case studies, the vertical cuts are automatically distributed across the major axis of prototype, while the horizontal ones are calculated to ensure the prototypes can be assembled. However, this approach does not consider the size, location, or fabrication times of the resulting parts, with the number of parts partially controlled through the number of vertical cuts. Therefore, it is unlikely that an optimum shell decomposition will be achieved. If the constraints on the perpendicularity of the cuts are removed, the calculations to generate the locations (and required rotations) of the planes becomes incredibly complex to ensure the assemblability of the prototypes. The relaxed perpendicularity constraint would mean that the vertical (Z+) assembly direction cannot be guaranteed, requiring careful consideration when calculating the assemblability and generating the instructions. It would also allow the designer to constrain the number of resultant parts (e.g. split into 10 printed parts), something that is unachievable in the current HP tool.

[167] Berg, M. de et al. (2008) *Computational Geometry: Algorithms and Applications*

The simulation based approach for the case studies was a valid approach as discussed in RQ1. The metrics used in the simulation experiments need to be discussed. The objects chosen fitted into the scope of the products considered in the thesis – i.e. form–based *user–driven* products. However, the generation of the iterations was performed artificially. While this offered control over the outcome, it is not necessarily representative of real-world design changes. For example, the prototype iterations used in Chapter 8 showed a much greater level of change. Nevertheless, the iterations used allowed the implementation of HP to be investigated and characterised across a different levels of detail.

From the shell decomposition, the number of resulting parts could not be directly controlled as the horizontal cuts (parallel to the X-Y ground plane) were calculated to guarantee that the prototype could be assembled. These cuts were required to ensure that the assembly would match the vertical (Z+) build direction of the underlying LEGO structure. Therefore, in the studies the number of vertical cuts (X-Z or Y-Z planes) was used as a proxy for the number of parts by assuming that more vertical cuts lead to more printed parts. This assumption holds true as Figures 6.13 to 6.15 show. Furthermore, the use of vertical cuts meant that cross object comparisons could be made over the case study objects – i.e. the fabrication time increases with the number of vertical cuts. If the HP tool is developed to accommodate less rigid constraints on the positions and rotations of the planar cuts, the results could be updated to better understand the relationship between part count and fabrication time.

9.2.3 Research Question 3

The third research question was:

> "How can the time and material savings of Hybrid Prototyping be maximised?"

Chapter 7 addressed Objectives 6 and 7. The sixth objective was to explore and establish the strategies for maximising the benefits of HP. To explore different strategies, three areas were identified as potential avenues to improve the HP outputs; adapting fidelity, distributing fabrication and managing reusability. From these, the different strategies and the interrelationships were mapped, before deciding which to focus on to investigate their effect. The seventh objective was to characterise the implementation of these strategies on the Hybrid Prototypes. The three strategies were taken from the three areas for improvement and were as follows:

- Adapted Fidelity HP
- Distributed Fabrication HP
- Reuse Focussed HP

Each of these was investigated through their application to the case study objects. Table 9.4 summaries the key findings from the results of these investigations.

Table 9.4 The key findings from Research Question 3

Finding	Description
Adapted Fidelity	Reducing fidelity outside ROIs reduces fabrication time. A fidelity level of 41.3 % was required to match the theoretical simulation result of a 45 % reduction in fabrication time.
Distributed Fab.	Significant reduction in fabrication time by using multiple printers, though diminishing returns beyond 10 printers. At least 3 printers were required to meet the 45 % reduction in fabrication time.
Reuse Focussed	Benefits dependent on scope and size of changes between iterations, small localised changes offer greatest reduction in fabrication time and increase in reusability. Increasing the number of printed parts, improved the results further.

Method & Limitations

The experimental setup was tailored to each strategy, and so each had their own methods and limitations. As a result, they will each be addressed in turn. However, what they all had in common was the simulation based approach developed in RQs 1 and 2. As this has been discussed and justified previously, this section will not address this point.

Adapted Fidelity HP

The regions of interest were manually selected by positioning cut planes to separate different parts of the geometry. In the HP methodology, this is a manual process for the designer as it is challenging to capture and predict design intent and how the regions of interest relate to the purpose of the current prototype iteration. Due to the manual nature of defining fidelity, three levels of fidelity (full, medium, and low, at an average of 100 %, 60.6 %, 25.2 % respectively) were investigated for each of the case study objects. This provided a reasonable range of data to investigate and characterise the effect of isolating regions of interest. It showed a strong correlation between the level of fidelity and reduction in fabrication time (compared to printing as a single part). However, more data at different fidelity levels and across different products would have likely increased the confidence in this relationship.

The fidelity measure was based on the surface area of the original geometry that was kept high fidelity in the resulting Hybrid Prototype. This is a simplified measure and does not adequately describe the selected regions of interests – it merely measures their extent. Despite this, it does provide a metric that permits comparison between the different prototypes. A potential solution for a better capture and measure of the ROIs is for the designer to use a 'brush' to paint different ROIs on to the 3D geometry. These can then be tagged with the feature, functionality and intent, and whether they need to persist over multiple iterations. It would provide a more intuitive interaction with the digital tool and manipulating the geometry.

Distributed Fabrication HP

Distributing the printing of the required parts offered the greatest benefits in reducing the fabrication times. The fabrication times appeared to follow an exponential decay with the number of printers. In cases where the number of printers exceeded the number of parts, there was no improvement from additional printers. When aggregated the results showed diminishing returns beyond 10 printers. The most significant reduction in fabrication times were achieved when going from 1 printer to 2–6 printers – especially if the capital and running costs of additional printers are considered. However, the number of printers required to minimise the fabrication time increased with the number of printed parts.

As discussed in RQ1, the enormous range of printer hardware and print settings results in high variability in the performance of printers. Consequently, the implementation of parallelising the printing of Hybrid Prototypes required several assumptions to reduce the complexity of the problem. Of which, the largest assumption was that there was no difference in print time between printing the parts sequentially or one at a time. By applying this assumption it meant that the bin-packing of parts across multiple printers did not need to consider the number of parts or the size of parts. This ignored the effect of travel moves (between separate parts on the same bed) or the time taken to remove parts from the print bed. Tools exist to reduce both these issues (Optimised bed packing [149], automated part removal [163]), and their inclusion in the parallelisation would improve the model and give results that more closely resemble real-world situations.

Reuse Focussed HP

The results from the investigation into Reuse Focussed HP were less explicit than those of the other two strategies investigated. The main reason for this was that measuring the 'amount' of change between two iterations was challenging, and so it was impossible to draw a statistical correlation between level of 'change' and fabrication time or reusability. Despite this, the investigation considered two types of change that are likely to occur between iterations:

- General changes – large changes in the overall form that affect the geometry of the whole prototype.
- Local changes – small, localised changes in form that only affect a small region of the prototype.

For the general changes, the first and third iterations of the case study objects were used. For the local changes, the third iteration had some local changes added to the geometry (e.g. modifying the surface detail of grip of the video game controller).

The results showed that for the general changes, only the LEGO could be reused in the next iteration, while for the local changes, a significant proportion of the printed parts could be reused as well as the LEGO – shown by an increase of 16.43 % in the reusability over normal HP and a −43 % reduction in fabrication time. This meant that if the de-

[149] Vanek, J. et al. (2014) *PackMerger: A 3D print volume optimizer*
[163] Schwartz, J. (2017) *How We're Building a Robotic 3D Printing Factory*

signer is focussing on making changes to a particular feature then the majority of the prototype can remain constant, only swapping out the changed printed parts.

Notwithstanding the above, it is challenging to predict the impact of using this Reuse Focussed HP as the designer intent cannot be captured, and the level of changes are difficult to measure. The results do show that the LEGO is less sensitive to the type of change and so can be fixed between iterations to form a platform to add and modify printed parts to test designs.

9.2.4 Aim

In summary, this research has answered Research Question 1 by simulating the potential improvements HP could bring to producing prototypes. It has answered Research Question 2 through the creation of the DfFA rules and implementation of HP in the case study objects. Research Question 3 has been answered by establishing and investigating different strategies for maximising the benefits of HP. Objective 8 is addressed in Chapter 8, bringing the findings from all three RQs together to demonstrate and characterise Hybrid Prototyping in a real–world prototyping process.

Therefore it can be argued that this research has achieved the aim of investigating and characterising the coupling of LEGO and 3D printing to reduce prototype fabrication and material usage while preserving appropriate fidelity. This has led to the contribution to knowledge of a the Hybrid Prototyping methodology, the characterisation of coupling LEGO and 3D printing, the exploration of the benefits of HP, and the demonstration of HP in real–world prototypes. The contributions to knowledge are described further in Section 10.2.

9.3 Generalisability

This thesis began with a general view of prototyping in the design process and how it can be improved. It is therefore appropriate to consider the generalisability of the Hybrid Prototyping and how it can be applied in a wider spectrum of situations be discussed.

Several constraints were applied to the scope of the research In order to meet the aim of this thesis. These included:

- The prototyping techniques to combine – i.e. LEGO and 3D printing.
- The types of product to be prototyped – i.e. consumer electronics.
- The stage in the design process – i.e. early stage *proof-of-concept* prototypes.
- The functionality of the prototypes – i.e. *form* based prototypes.

The constraints on the scope allowed the investigation and characterisation of LEGO and 3D printing Hybrid Prototyping to be achievable within the time and cost bounds of the research project. However, this means the wider generalisability of the research and the findings need to be considered.

9.3.1 Prototyping Techniques

The concept of Hybrid Prototyping can be applied to many different prototyping techniques. In Chapter 3, some potential combinations of techniques were posited. However, the choice of using LEGO and 3D printing to explore HP was justified for several reasons: similarity of materials, achievable tolerances, health and safety, and low cost of machinery. Consequently, the Hybrid Prototyping methodology was developed through the lens of these two prototyping techniques. The two areas that would need to be adapted for a different combination of techniques are:

- Design rules – These focus on creating practically implementable prototypes by providing design rules focussed on the assemblability and printability of the resulting prototypes.
- Digital tool – This relies on the input geometry being a digital file, and the cuboid, orthogonal constraints of LEGO bricks to generate the necessary parts and instructions to create HPs.

The diagram of the high–level Hybrid Prototyping methodology (see Figure 8.1) offers a starting point for considering how to adapt the design rules and digital tool for different prototyping techniques to ensure their coupling and fabricability.

Design Rules

The design rules for Hybrid Prototyping are introduced in Chapter 6, offering three different types of rules and constraints to consider:

- *Technical Constraints* – fixed constraints that cannot be impacted by the actions of the designer – i.e. assemblability of the prototype; availability of parts/materials.
- *Design Considerations* – aspects that the designer must take into account when specifying the form, shape and geometry of the prototype – i.e. dimensional limits; resolution/scale of surface detail.
- *Process Considerations* – decisions the designer needs to make about how the Hybrid Prototype is fabricated – i.e. number of parts; location of part boundaries.

The relationship between these, and how they impact the resulting HPs can be seen in Figure 9.3. Where the 'process planning' is how the prototype is fabricated, and the 'prototype geometry' is the limitations on the geometry used for the HP.

In order to implement HP with different prototyping techniques, the three areas need to be re-addressed for the required techniques. These can be summarised by the two elements of the general Hybrid Prototyping methodology (see Figure 8.1): Coupling, and Fabricability – i.e. how to combine the techniques and ensure that the prototypes can be fabricated.

Digital Tool

In its current form, the digital tool requires significant redevelopment to make it applicable to Hybrid Prototyping with other techniques. As a result, the tool is not generalisable

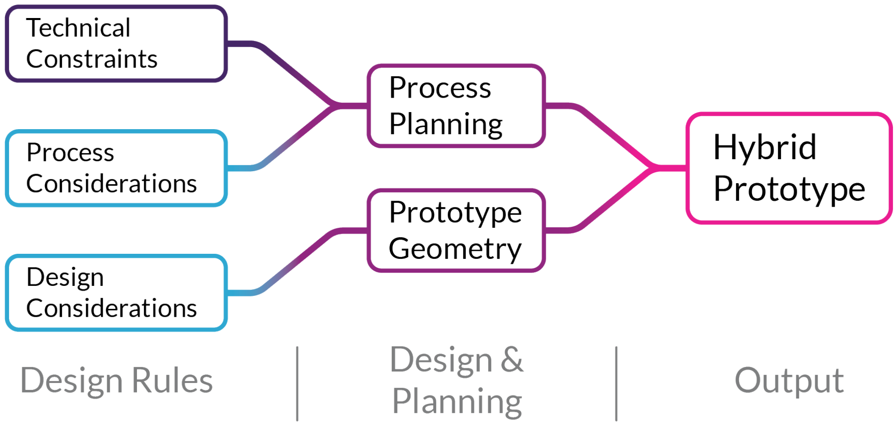


Figure 9.3 The relationship between the design rules and the resulting Hybrid Prototype

and needs to have functionality specific for the prototyping techniques used. For example, the algorithms for calculating and generating the LEGO structure would be very different to those to calculate how a truss construction kit (e.g. Meccano), or laser cut frame, or cardboard structure would be used within the geometry. However, algorithms do exist to create 3D objects with these techniques (e.g. Platener [110] for laser cut plastic sheets; Crdbrd [111] for cardboard objects) and so these could be incorporated into the digital tool.

In the research reported, the tool development was guided by the DfFA rules created for LEGO and 3D printed HPs. It follows that when the design rules are adapted for other techniques they can direct the development of the new digital tool.

9.3.2 Types of Product

As stated in Chapter 1, the scope of this thesis was on *user-driven* products (see Figure 1.3). These products often use their form and appearance for product differentiation. Consequently, being able to rapidly prototype form, user interaction, and ergonomics in the design of these products is crucial. The case study objects used in this research are consumer electronics that have a focus on interaction. Hybrid Prototyping works well in these scenarios – offering fast fabrication and high fidelity to quickly test designs. This form-based prototyping could be extended to scale models of large products, i.e. architectural models of buildings; scale models of aircraft. In these cases, the appearance and form are the key drivers in the purpose for prototyping and the findings from investigating HP can be applied. This shows that HP can be generalised across classes of products, providing form-based prototypes are used.

9.3.3 Stage in the Process

The Hybrid Prototyping methodology has focussed on *proof–of–concept* prototypes (according to Ullman's [25] classifications). The reason for targeting these prototypes is that

[110] Beyer, D. et al. (2015) *Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates*
[111] Hildebrand, K. et al. (2012) *crdbrd: Shape Fabrication by Sliding Planar Slices*
[25] Ullman, D. G. (2003) *The Mechanical Design Process*

75 % of product cost is committed in the early stages of the design process, and offers the greatest opportunity for reducing development costs. As the design process progresses from conceptual design into embodiment and then detail design, the requirements from a prototype become more specific and targeted towards manufacturability and optimisation of the design. The prototyping techniques used in Hybrid Prototyping cannot meet these requirements. As the design more closely represents the final production design the prototypes become more sophisticated and use materials, assemblies and techniques that prove the design can be produced – i.e. *proof–of–production* or *integration* prototypes (see Sections 1.2.2 and 2.2.1 respectively).

As such, the implementation of HP and the findings reported are more applicable to the early stages of the design process and they cannot be more generally applied to later stages of the design process. It is in the early stages where the reduction of fabrication time and material costs can have significant impact on the cost of developing the product.

9.3.4 Level of Functionality

Due to the nature of the products investigated (i.e. *user–driven*) and the physical prototyping techniques used (i.e. LEGO and 3D printing), the prototypes considered were form-based – fitting into Houde and Hill's [56] *look–and–feel* classification (see Figure 2.1). This limited the HP methodology to producing non-functional prototypes that designer could use to quickly test the form, user interaction and appearance of the designs in a physical and tangible way.

Consequently, the findings can not be generalised to consider how a Hybrid Prototyping methodology would produce functional prototypes and what the effect on fabrication time and material use would be. Section 9.4.2 considers how the current LEGO and 3D printing approach could be expanded to produce more mechanically functional prototypes.

9.4 Future Work

The primary focus of this thesis has been to investigate and characterise Hybrid Prototyping. However, during the research several avenues for future research emerged. The avenues can be loosely grouped into three categories:

- *Activity* – the affect of HP on the design activities of prototyping within the design process.
- *Tool* – further improvements to the HP tool.
- *Use* – the user experience/workflow of the HP tool.

From these categories more specific areas for future research were identified. These areas include:

[56] Houde, S. and Hill, C. (1997) *What do prototypes prototype?*

- Application of HP in the design process (*Activity*).
- Continued development of the HP tool (*Tool*).
- Automation and deskilling of HP methodology decisions (*Use*).

The following sections summaries each of these three areas and offer future research questions.

9.4.1 Application of HP in Design Process

The research reported in this thesis considers the development and practical benefits of implementing Hybrid Prototyping. It does not consider how designers would use the HP methodology in a design task. Investigating how the inclusion of HP would change the design process and reduce production costs would be the next step. The investigation could include quantitative data of the impact on number of iterations, fabrication time, material costs, as well as qualitative data on the designers' thoughts and considerations when using the HP tool. This leads to the future research question: how does the inclusion of HP affect designers and the design process?

Another aspect to investigate is the effect of physical editing on the Hybrid Prototypes and how it supports the designers' thinking. One of the affordances of creating HPs is the ability to physically edit and modify the designs by swapping out parts or adding LEGO bricks. While the modifications are limited by the resolution of the LEGO, it could bring benefits to designers and stakeholders alike. It follows that it would be a worthwhile area to investigate, through the research question of how does performing physical modifications to the prototypes affect the design process?

9.4.2 Continued Development of the Tool

Two areas of the digital tool could be developed to improve its functionality and increase the benefits of Hybrid Prototyping.

The first is to expand the library of bricks beyond the standard bricks (see Figure 4.4) to include the curved, sloped, and other non-cuboid bricks. Their inclusion in the digital tool would provide a better approximation of the target geometry and reduce the fabrication time and increase the reusability of the prototypes. Similarly, there are bricks that allow the build direction to change through 90° so that bricks (and printed parts) do not have to be added in a vertical order. This expansion of the available bricks leads to the future research question: how does the use of non-standard bricks affect the fabrication time and material use?

The second area is to incorporate LEGO Technic into the digital tool. LEGO Technic provides linkages, axles, and gears to create mechanisms. These could be used to add some mechanical functionality into the prototypes. This leads to two research questions:

- How can the desired mechanical movement of the prototype be captured and created in the Hybrid Prototype?

- How do mechanically functional Hybrid Prototypes affect the prototyping process?

9.4.3 Automation of Tool Decisions

Chapter 8 discussed the different decision factors and variables to achieve particular design goals when Hybrid Prototyping. However due to requiring knowledge about the effects of HP and the variables to set, this can be challenging to manage and to achieve the desired results. By automating (or at least guiding) these decisions, the skill barrier to using HP is lowered – democratising the creation of prototypes. This would increase the usability allowing non-technical stakeholders to create Hybrid Prototypes. This avenue of future work raises two research questions:

- How can designer prototyping intent be mapped to the necessary HP variables?
- What impact does automating the decisions in the HP methodology have on the usability of the tool?

9.4.4 Summary of Future Work

The avenues for future work described here offer a brief overview of the direction of future research beyond what has been described in this thesis. Table 9.5 highlights the future research questions identified in this section.

Table 9.5 Future research questions

Future Research Questions
How does the inclusion of HP affect designers and the design process?
How does performing physical modifications to the prototypes affect the design process?
How does the use of non-standard of bricks used affect the fabrication time and material use?
How can the desired mechanical movement of the prototype be captured and created in the Hybrid Prototype?
How do mechanically functional Hybrid Prototypes affect the prototyping process?
How can designer prototyping intent be mapped to the necessary HP variables?
What impact does automating the decisions in the HP methodology have on the usability of the tool?

Chapter 10

Conclusion

10.1 Fulfilment of the Aim

The aim of the thesis was:

> "To investigate and characterise the coupling of LEGO and 3D printing to reduce prototype fabrication time and material use, while preserving appropriate fidelity."

This aim was fulfilled through the development of a LEGO and 3D printing Hybrid Prototyping methodology. In order to investigate and characterise the methodology, the aim was broken down into three research questions. These research questions were answered through iterative development and evaluation of the methodology in Chapters 5 to 7 respectively. These chapters addressed the following questions:

1. What are the potential time and material savings from Hybrid Prototyping?
2. How can Hybrid Prototyping be implemented in practice?
3. How can the time and material savings of Hybrid Prototyping be maximised?

The research presented in this thesis answered Research Question 1 by simulating the potential improvements HP could bring to producing prototypes. It answered Research Question 2 through the creation of the DfFA rules and implementation of HP in the case study objects. Research Question 3 has been answered by establishing and investigating different strategies for maximising the benefits of HP. The key findings, methods and limitations for each RQ were discussed in Sections 9.2.1 to 9.2.3 respectively. Chapter 8, linked the findings from all three RQs to demonstrate and characterise Hybrid Prototyping in a series of prototypes used in the development of a real–world product.

Therefore this thesis has met the aim of investigating and characterising the coupling of LEGO and 3D printing to reduce prototype fabrication and material usage while preserving appropriate fidelity. This has led to the contribution to knowledge of the Hybrid Prototyping methodology, the characterisation of coupling LEGO and 3D printing, the exploration of the benefits of HP, and the demonstration of HP in real-world prototypes. The contributions are described further in the following section.

10.2 Contributions to Knowledge

The author's overall contributions to knowledge from the thesis are outlined in this section. The four key areas that show these contributions are:

1. The Hybrid Prototyping Methodology
2. Characterisation of coupling LEGO and 3D printing
3. Exploration of the benefits
4. Demonstration of Hybrid Prototyping

These are described in more detail in the following sections.

10.2.1 Hybrid Prototyping Methodology

The first and main contribution to knowledge from this thesis is the development of the Hybrid Prototyping Methodology. This describes a *disruptive approach* to prototyping (see Section 2.4.3) that couples complementary prototyping tools to combine their benefits and affordances, while mitigating their limitations. The overall Hybrid Prototyping methodology is presented in Figure 8.1 and described in Section 8.2. The methodology describes the general process for creating Hybrid Prototypes, including the inputs, considerations, and decisions needed to implement the methodology. While the research reported in this thesis is an instantiation of the methodology using LEGO and 3D printing, the overall methodology provides a guide for creating other forms of Hybrid Prototypes.

A key part of this contribution is the development of the Design for Fabrication and Assembly Rules (DfFA) for coupling LEGO and 3D printing, and the strategies for maximising the benefits of HP. These provide an original framework for the rules and strategies for creating Hybrid Prototypes. While these were developed to be specific to LEGO and 3D printing, the underlying relationships between the constraints, considerations, and resulting HPs was established (see Figure 9.3) could be applied to other techniques.

The codification of the methodology was implemented in the digital tool – an open source add-on for Blender 2.79 [168]. The add-on provides all of the functionality to create and export Hybrid Prototypes from 3D geometry within Blender. Through the custom graphical user interface all of the variables (as discussed in Chapter 8) can be set and applied to the Hybrid Prototypes. This tool provides a prototyping platform that allows other users to create HPs, investigate their impact on the design process, and develop the methodology further.

The creation of the HP methodology, and subsequent investigation of its implementation, demonstrates and verifies the framework – contributing a validated methodology for Hybrid Prototyping to the field of prototyping research.

10.2.2 Characterisation of LEGO and 3D Printing

The second contribution to knowledge is the characterisation of coupling LEGO and 3D printing in the Hybrid Prototyping methodology. This builds on the development of the Hybrid Prototyping methodology, using it as a platform to explore and experiment with the disruptive approach to prototyping. The characterisation offers novel insight into how the coupling of these two techniques can reduce prototype fabrication time and material usage. The characterisation is comprised of three elements:

- The affect of relative brick size on the fabrication time and level of reusability of Hybrid Prototypes. The optimum brick–to–object ratio was found to be in the range 1:2500 - 1:1250, reducing the fabrication time by 45 % and a reusability of 55 %. These results were discussed in Section 5.4.

[168] Mathias, D. (2019) *Brixelate Blender Add-on*

- The requirements and constraints for feasibly implementing HPs. However, the implementation resulted in an average increase of 26.63 % in fabrication time over 3D printing. The performance of HP was discussed in Section 6.5.3.
- The identification and impact of different strategies for maximising the benefits when using HPs. These strategies were Adapted Fidelity, Distributed Fabrication, and Reuse Focussed HP, as first established in Section 7.2. Their contributions are outlined in Section 10.2.3.

This thesis reports the findings of the characterisation and contributes this knowledge to the field of prototyping research.

10.2.3 Exploration of the Benefits

The third contribution to knowledge is the exploration of the benefits of and strategies for Hybrid Prototyping. Different strategies for maximising the benefits of Hybrid Prototyping were investigated in Section 7.3. The three strategies were:

- Adapted Fidelity (AF) HP – changing the level of fidelity of the prototype to reduce the number and volume of printed parts.
- Distributed Fabrication (DF) HP – distributing the 3D printed parts over multiple printers.
- Reuse Focussed (RF) HP – managing the reusability of bricks and printed parts between iterations.

Using these strategies, the benefits in fabrication time, material costs, and fidelity in HPs were explored and discussed in the three case study objects. The results showed:

- AF – Lower fidelity meant lower fabrication time and material costs. A fidelity of 41.3 % was required to match the 45 % reduction in fabrication time shown in Chapter 5.
- DF – More printed parts offered greater scope for distributing the printing. Significant reduction in fabrication times when using 2–6 printers, with diminishing returns beyond 10 printers. At least 3 printers were required to match the 45 % reduction in fabrication time shown in Chapter 5.
- RF – Increasing the number of printed parts increased the reusability in situations with small, localised changes. Compared use in general and local changes, with RF working best in local changes with a 43.4 % reduction in fabrication time and a 16.4 % increase in reusability over normal HP.

These strategies were then implemented in real–world prototypes. From this, the benefits of different HP strategies were compared against 3D printing the prototypes whole. This generated knowledge about how the different strategies can be used to meet different goals designer's have when prototyping.

10.2.4 Demonstration of Hybrid Prototyping

The final contribution to knowledge was the demonstration and validation of Hybrid Prototyping in a series of real–world prototypes. These were part of the product development process for an automatic light fitting, called See Sense. While HP has been demonstrated in several scenarios and objects over the course of the development, the application of HP in real–world prototypes provides a validation case for the methodology.

The application of the three HP strategies in the See Sense prototypes was described in Section 8.3. The results when compared to printing the prototypes as a single part were as follows:

- Distributed Fabrication – 56.09 % reduction in fabrication time, 60.03 % reduction in material usage.
- Adapted Fidelity – 12.37 % reduction in fabrication time, 76.22 % reduction in material usage.
- Reuse Focussed – 27.38 % increase in fabrication time, 61.96 % reduction in material usage.

These results were discussed in Section 8.3.3, but overall they validate the coupling LEGO and 3D printing as an instantiation of the HP methodology. The validated HP methodology is a contribution to the field of prototyping research.

10.3 Summary of Thesis

To conclude the thesis, the research is summarised. Following the introduction in Chapter 1, Chapter 2 describes an extensive literature review of prototyping techniques, classification of prototypes, and existing research to improve prototyping in the design process. It showed that physical prototyping is critical to design process, acting as a learning and communication tool for designers and stakeholders. It was also found that the biggest barriers to its use are the cost and time required to produce prototypes. While there has been significant research into improving prototyping, this has mostly focussed on the process of prototyping and frameworks to support it. There has been little research into how to improve individual techniques. The literature review demonstrated that there is no single technique that affords high fidelity prototypes, that can be rapidly fabricated while offering flexibility and reconfigurability required in the early stages of the design process. The thesis addresses this shortcoming through the development of Hybrid Prototyping.

Chapter 3 introduced the concept of Hybrid Prototyping. The idea to combine complementary prototyping techniques arose from a study that compared sketching, CAD, cardboard modelling and LEGO in a group design task. The findings from the study showed that the cost of modifications hindered design iterations, and that low fidelity prototypes were ambiguous and more challenging to communicate. Consequently, combining techniques was posited as a solution to the tension between faster and cheaper prototypes and higher fidelity prototypes. Potential combinations were considered, LEGO and 3D printing were chosen as the techniques to use to investigate Hybrid Prototyping.

Chapter 4 introduced the thesis aim and broke it into three research questions:

1. What are the potential time and material savings from Hybrid Prototyping?
2. How can Hybrid Prototyping be implemented in practice?
3. How can the time and material savings be maximised?

This chapter also justified the simulation-based method and objects used to investigate Hybrid Prototyping, and briefly explained the software and hardware technology platforms employed. Chapters 5 to 7 answered the three research questions respectively, with Chapter 8 tying all three together in a demonstration of the overall Hybrid Prototyping methodology.

Chapter 5 described the development of the initial algorithms (*Brixellation, Packing, Shelling*) for the HP methodology. These are then used to investigate the potential benefits of HP in a simulation study in order to answer RQ1. The findings showed a potential reduction in fabrication of 45 % at a reusability of 55 %.

Chapter 6 established the design rules for Hybrid Prototyping. DfAM and LEGO build rules were reviewed and the relevant aspects drawn into the DfFA rules. These rules allowed the further development of the digital tool to be able to implement HPs. The updated tool was used to investigate the feasibility of fabricating the prototypes. The results showed that while feasible, the fabrication times were slower than simulated in Chapter 5, due to the increased surface area of the printed parts.

Chapter 7 considered different areas for improving the benefits of using HP when prototyping and mapped the interrelationships between the different factors. From this, several strategies were identified with three being chosen to be investigated. These were: preserving regions of interest; distributing the printing across multiple printers; and managing reuse between iterations. All of the strategies could match the results from Chapter 5 and offered significant benefits over simply printing the prototypes, with distributed printing offering the greatest benefits of −75 % change in fabrication time (with 9 printers). However, there were caveats to the strategies and their benefits and limitations in different scenarios was discussed.

The overall Hybrid Prototyping methodology was described and demonstrated in Chapter 8. The digital tool, its user interface, and workflow were explained in detail, including the design decisions the designer must make to achieve particular prototyping goals. Next the methodology was demonstrated in a series of real-world prototype for an automatic light fitting called See Sense. Distributed printing gave the greatest mean reduction in fabrication time of −56.09 %, while adapting the fidelity saved the most material over all the iterations at −76.22 % over printing them as single parts.

The research reported in the thesis was discussed in Chapter 9. The fulfilment of the thesis aim was discussed and shown to have been met through the answering of the three research questions and their objectives. For each research question, the findings and their implications were presented, along with a discussion around the method and limitations for the studies undertaken. As the scope of the research was limited to ensure the feasibility of the work, the generalisability beyond the constraints of the thesis was considered. This was addressed in four areas: the techniques used; the types of products; the stage in the design process; and the functionality of the prototypes. Following this, potential avenues of future work were posited, along with corresponding research questions to investigate in the next stages of this research.

Chapter 11

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Appendix A

Supplementary Information

Table A.1 An example of the self reporting form used in the prototyping comparison study

	None (0 min)	Some (1–3 min)	A Lot (5–10 min)
Problem Structuring			
Ideating, Generating new ideas			
Refining, Developing ideas			
Evaluating, Critiquing ideas			
Collaborative Work			
Other (Describe)			

Table A.2 The standard library of LEGO bricks with their dimensions expressed as numbers of base bricks

Plates Name	Dimensions	Bricks Name	Dimensions
6 x 2	[6 2 1]	6 x 2	[6 2 3]
4 x 2	[4 2 1]	4 x 2	[4 2 3]
3 x 2	[3 2 1]	3 x 2	[3 2 3]
2 x 2	[2 2 1]	2 x 2	[2 2 3]
6 x 1	[6 1 1]	6 x 1	[6 1 3]
4 x 1	[4 1 1]	4 x 1	[4 1 3]
3 x 1	[3 1 1]	3 x 1	[3 1 3]
2 x 1	[2 1 1]	2 x 1	[2 1 3]
1 x 1	[1 1 1]	1 x 1	[1 1 3]

Appendix B

Publication Abstracts

Accelerating product prototyping through hybrid methods: Coupling 3D printing and LEGO

Mathias, D., Snider, C., Hicks, B., and Ranscombe, C.

Design Studies

(2019)

Abstract

This paper introduces Hybrid Prototyping as a way to couple different prototyping methods; combining their complementary affordances and mitigating their limitations. To characterise and investigate this approach, a simulation-based study was conducted into the coupling of low-cost 3D printing and LEGO. Key benefits hypothesised are reduced fabrication time and increased reconfigurability. Six primitive 3D shapes are simulated using a continuum of hypothetical brick sizes. Results show a reduction in fabrication time of 45% and a reconfigurability of 57% at the optimum. A case study highlights the compounded improvements over 3D printing for an iterative prototyping process. These findings mean that increases in prototyping iterations can be made due to reduced time and material costs, accelerating the product development process.

Designing with LEGO: exploring low fidelity visualization as a trigger for student behavior change toward idea fluency

Ranscombe, C., Bissett-Johnson, K., Mathias, D., Eisenbart, B., and Hicks, B.

International Journal of Technology and Design Education

(2019)

Abstract

Novice design students struggle to engage with early stage design visualization tools such as sketching and prototyping. Instead students have a preference for designing with digital tools such as CAD modelling, motivated by inhibitions around sketching skill, which in turn leads to fixation and sunk cost effects. These behaviors present a barrier to engag- ing in typical practices of expert designers, namely idea fluency described as generating a wide range of ideas quickly and avoiding favoring one single idea. Noting the recent suc- cess of LEGO Serious Play in engaging non-designers in design activities in business and innovation contexts, we explore whether using LEGO as a visualization tool can trigger a behavior change in student designers towards idea fluency. This paper presents a study comparing student attitudes and design behavior when designing with LEGO, in compari- son to sketching and cardboard modelling. Findings illustrate how LEGO's comparative low fidelity leads to students to be more willing to change and modify initial ideas, reduces inhibitions related to visual quality, and reinterpret and iterate designs. Based on these findings we illustrate how designing with LEGO can mitigate issues of inhibition, fixation, and sunk cost design behaviors concluding that LEGO can trigger behavior change toward idea fluency. As such we see compelling evidence to integrate LEGO as an educational design activity for novice designers used early in the design process to illustrate and trigger idea fluency.

Hybrid Prototyping: Pure Theory or a Practical Solution to Accelerating Prototyping Tasks?

Mathias, D., Hicks, B., and Snider, C.

Proceedings of the Design Society: International Conference on Engineering Design

(2019)

Abstract

Physical prototyping is critical activity in the produce development process, but the cost and time required to produce prototypes hinders it use in the design process. Hybrid prototyping through coupling LEGO and FDM printing is presented as an approach to address these issues. After establishing the separate design rules for FDM printing and LEGO, this paper created new set of rules called Design for Fabrication (DfF) for hybrid prototyping. These cover the three main considerations (Technical, Process, and Design) that the designer and process planning must include to practically implement LEGO and FDM hybrid prototyping. The DfF rules were considered in a prototype of a computer mouse. While the fabrication time was not reduced as expected, it showed that the rules could be practically implemented in a real-world example. Additional considerations were identified that are to be included in the DfF rules.Further work is required to realise the predicted step-change reduction in fabrication time. The first approach is to leverage multiple printers to parallelise the printing. The second is to reduce fidelity while maintaining high fidelity in key regions of interest.

Characterizing the Affordances and Limitations of Common Prototyping Techniques to Support the Early Stages of Product Development

Mathias, D., Hicks, B, Snider, C, and Ranscombe, C

International Design Conference - Design 2018

(2018)

Abstract

The act of prototyping is more than the artefact produced – the process helps answer design questions. A knowledge of prototyping activities leads to better decisions in the design process. The aim of this paper is to characterise and compare prototyping techniques. A literature review explores current research into characterising prototypes, before highlighting the need for comparison. A study is reported that compares the design activity of sketching, CAD, cardboard and LEGO when used as prototypes in a group design task, showing differences in the levels of different design activities.

Design Variation through Richness of Rules Embedded in LEGO Bricks

Mathias, D., Boa, D., Hicks, B. J., Snider, C., Bennett, P., and Taylor, C.

Proceedings of 21st International Conference on Engineering Design, ICED 2017

(2017)

Abstract

Design rules govern the design process by imposing constraints on the development of a product. Examples of design rules include engineering standards, regulations, standard operating procedures and existing designs as protected by patents. They have the potential to over-constrain the design space and impact innovation. In this paper, an exploratory study is reported that investigates the link between richness of design rules and the resulting design variation in a LEGO model. Design rule richness describes the quantity and explicitness of constraints relating to a design. Design rules, relating to a model of a simple spaceship, were embedded in individual LEGO bricks. Twenty participants were tasked with constructing the spaceship while adhering to the set design rules. There were four levels of design rule richness and the participants constructed a model for each level. Measuring the design variation through Design Structure Matrices revealed that the richness of the design rules only had a significant effect on the design variation between the least and most rich design rules. This suggests that a point exists at which the richness of design rules limit design variation.

Digital Sketch Modelling: Proposing a Hybrid Visualisation Tool Combining Affordances of Sketching and CAD

Ranscombe, C., Zhang, W., Rodda, J., and Mathias, D.

Proceedings of the Design Society: International Conference on Engineering Design

(2019)

Abstract

Visualisation of ideas and emergent designs is an essential ingredient in design practice. Sketching and CAD represent two widely used visualisation tools, each with complementary affordances that dictate their typical use during the design process. Sketching has affordances of fast and fluent visualisation whereas CAD affords easy modification of detailed designs. This paper proposes a hybrid tool, Digital Sketch Modelling, investigating the extent to which it can deliver complementary affordances of both sketching to CAD. Analysis of diary entries made by 62 postgraduate designers using sketching, digital sketch modelling and CAD within a design project forms the basis of the study. Results illustrate how digital sketching over crude 3d digital models, combined with benefits of digital image editing software enhance affordance for easy visualisation of ideas. Concurrently, the level of software used in Digital Sketch modelling led to fewer concerns over the level of difficulty to modify designs, enhancing the affordance for easy modification. As such we conclude Digital Sketch Modelling does combine affordances indicating its potential benefit in use between sketching and CAD.

Evolving lego: Prototyping requirements for a customizable construction kit

Boa, D., Mathias, D., and Hicks, B.

Proceedings of 21st International Conference on Engineering Design, ICED 2017

(2017)

Abstract

The PhysiCAD project is a technical feasibility study into the creation of tangible interfaces for Computer Aided Design (CAD) using construction kits. Construction kits, such as LEGO, are a collection of pre-defined physical elements that can be combined using standardised interfaces to produce more complex artefacts. Construction kits like LEGO have a low skill threshold to start using and are highly reconfigurable. The aim of the PhysiCAD project is to merge the benefits of construction kits with CAD. This paper concentrates on one aspect of the PhysiCAD project, how construction kits can be changed to support the representation of physical concepts. To this end we propose the concept of an evolving construction kit with the capability to define and generate new element types within the system. In this paper five requirements for an evolving construction kit are identified along with technical solutions for implementing them. Examples of some of the technical solutions are included along with a discussion about how they could be used to generate new evolved construction kit elements.

Realisation of self-replicating production resources through tight coupling of manufacturing technologies

Goudswaard, M., Hicks, B. J., Nassehi, A., and Mathias, D.

Proceedings of 21st International Conference on Engineering Design, ICED 2017

(2017)

Abstract

The purpose of this paper is to explore the implications of the tight coupling of manufacturing technologies and the extent to which it can facilitate the realisation of self-replicating production resources. This was explored through a three year programme of development projects where multiple 3D printing and milling machines were designed, built and evaluated with respect to their manufacturing capabilities and self-replicability. It was found that this tight coupling of processes increased functionality, self-replicability and consequentially utility of these machines. The project specifications were used to identify conflicting requirements and qualitatively assess their interrelationships. Further work will see this expanded into a quantitative model to identify where design effort should be focused and also theoretical limits of self-replicability. The principal social implication of this work is that nonautotrophic self-replication, upon which the RepRap philosophy is based, is largely dependent upon locally available technology and resources. Self-replication therefore becomes an affordance of not solely machine but also of environment.

Colophon

The main text of this thesis was typeset in 11pt Vollkorn, with headings, captions, and footnotes set in various sizes of Lato. The typesetting was performed by the author using LuaTeX.

The bibliography was typeset using BibTeX. The graphics were designed in Adobe Illustrator CC, the rendered images generated in Blender 2.79, and the plots generated in Python 3.7 with Matplotlib 3.1.1.

The colour scheme was as follows:

C	50.20 %	69.80 %	87.45 %	50.20 %	41.96 %
M	100.0 %	16.08 %	100.0 %	100.0 %	34.12 %
Y	13.73 %	08.24 %	27.45 %	13.73 %	34.51 %
K	01.18 %	00.00 %	16.86 %	01.18 %	23.00 %